MINOS

Luke A. Corwin, for MINOS Collaboration
Indiana University

XIV International Workshop On Neutrino Telescopes

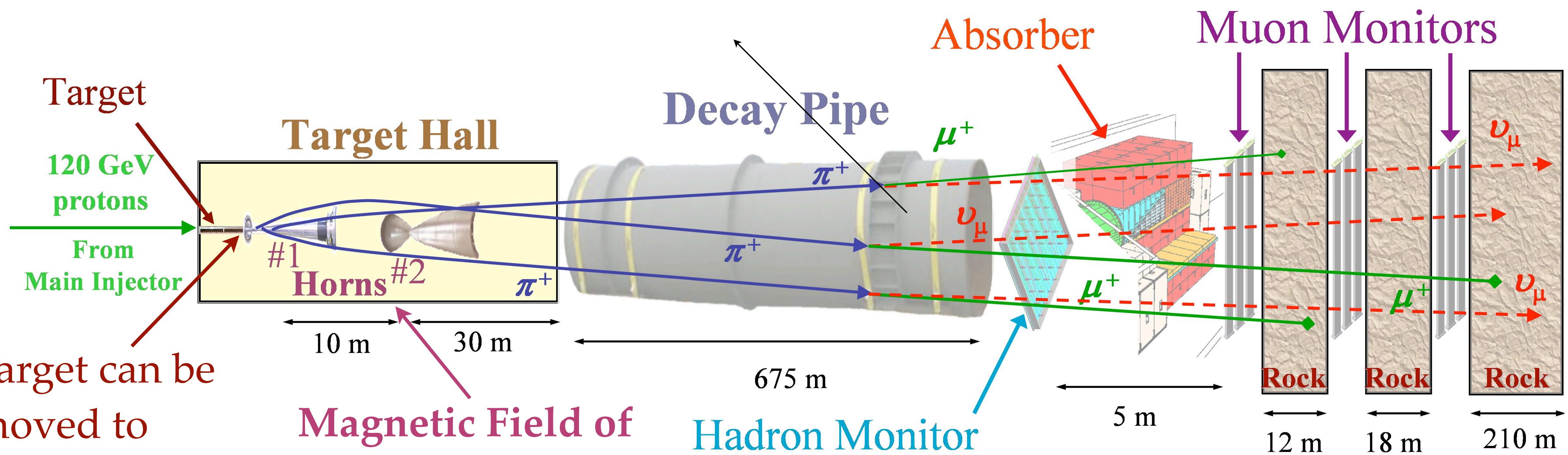
2011 March 15

Overview and Current Status

- Beam
- Detectors
- Analyses
  - Neutrino Charged Current
  - Anti-neutrino Charged Current
  - Electron Neutrino Appearance Analysis
  - Quasi-Elastic Scattering
  - Atmospheric Neutrinos

The Beam

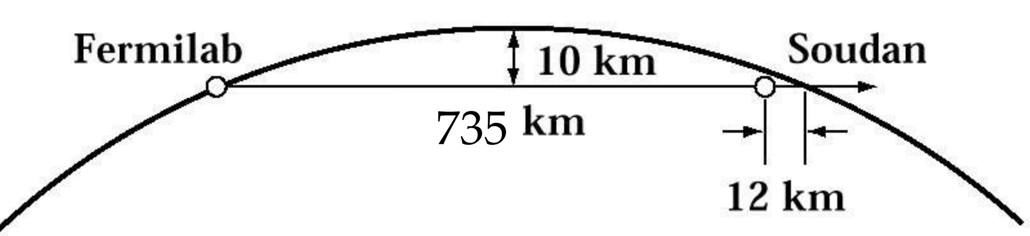
- Small cross section ⇒ we need large number of neutrinos ⇒ we need an intense beam



Target can be moved to produce different neutrino energy spectra

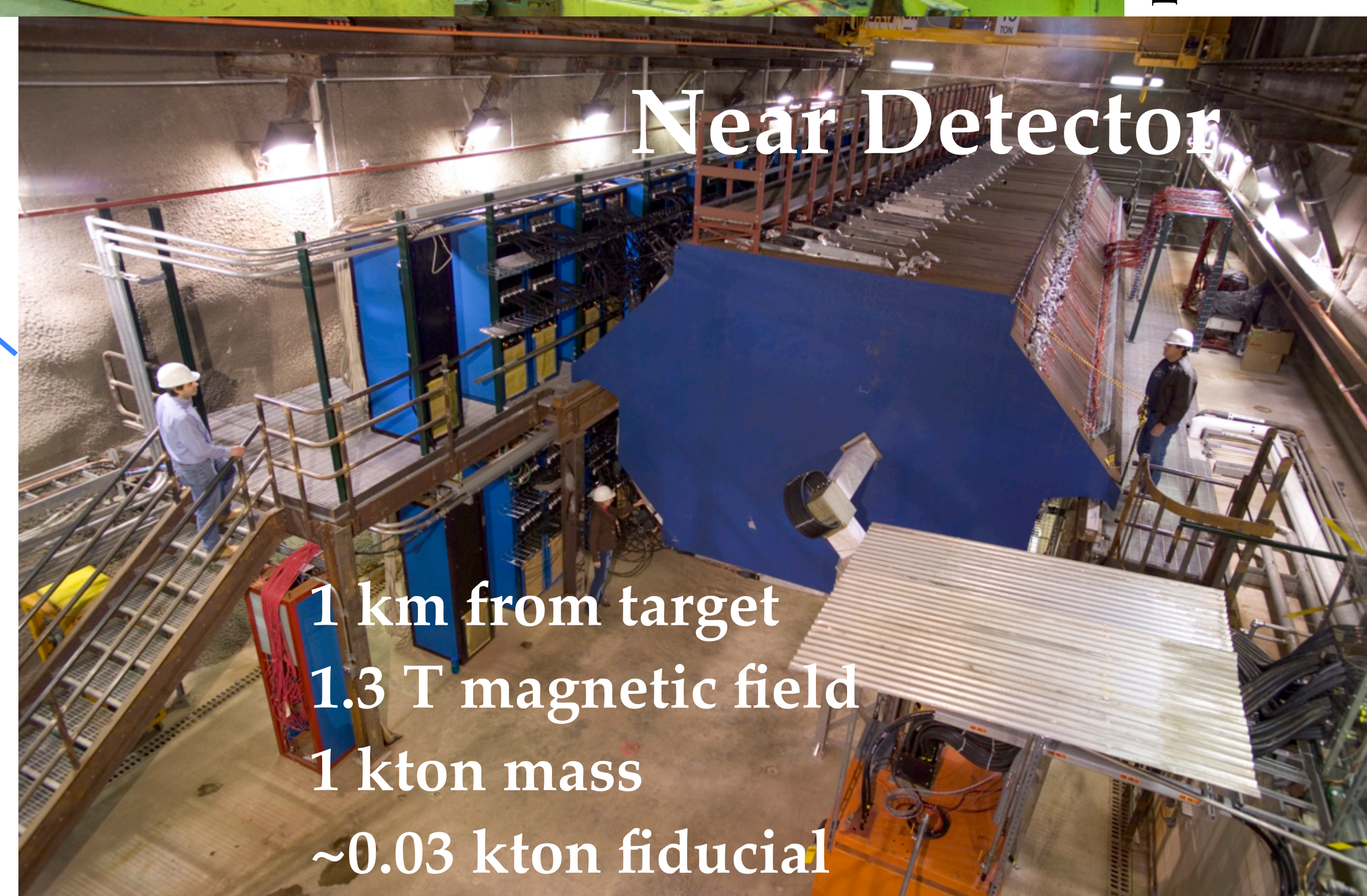
Magnetic Field of Horns can be reversed to produce antineutrino beam

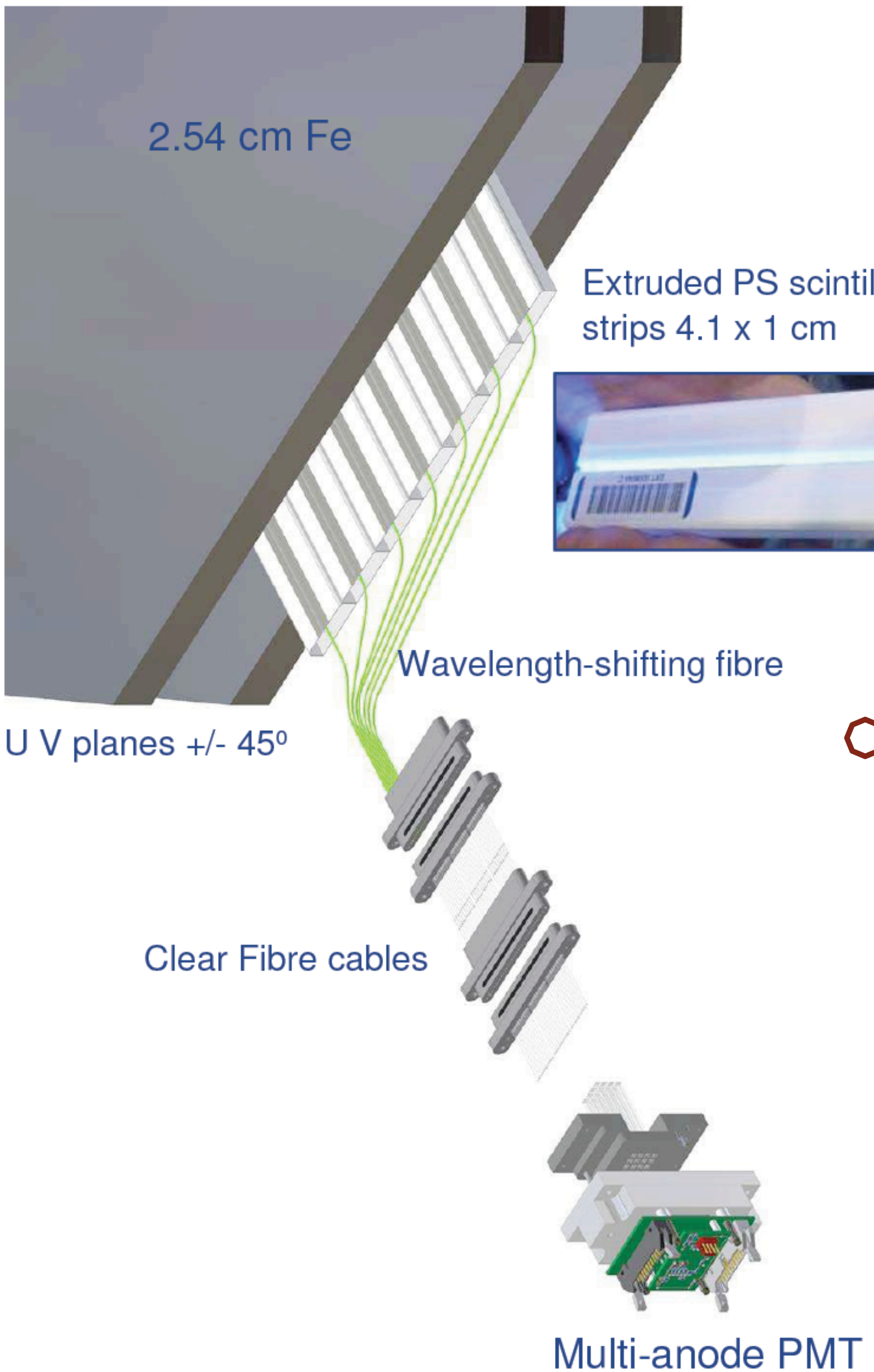
http://www.hep.ucl.ac.uk/minos/minosmap.jpg

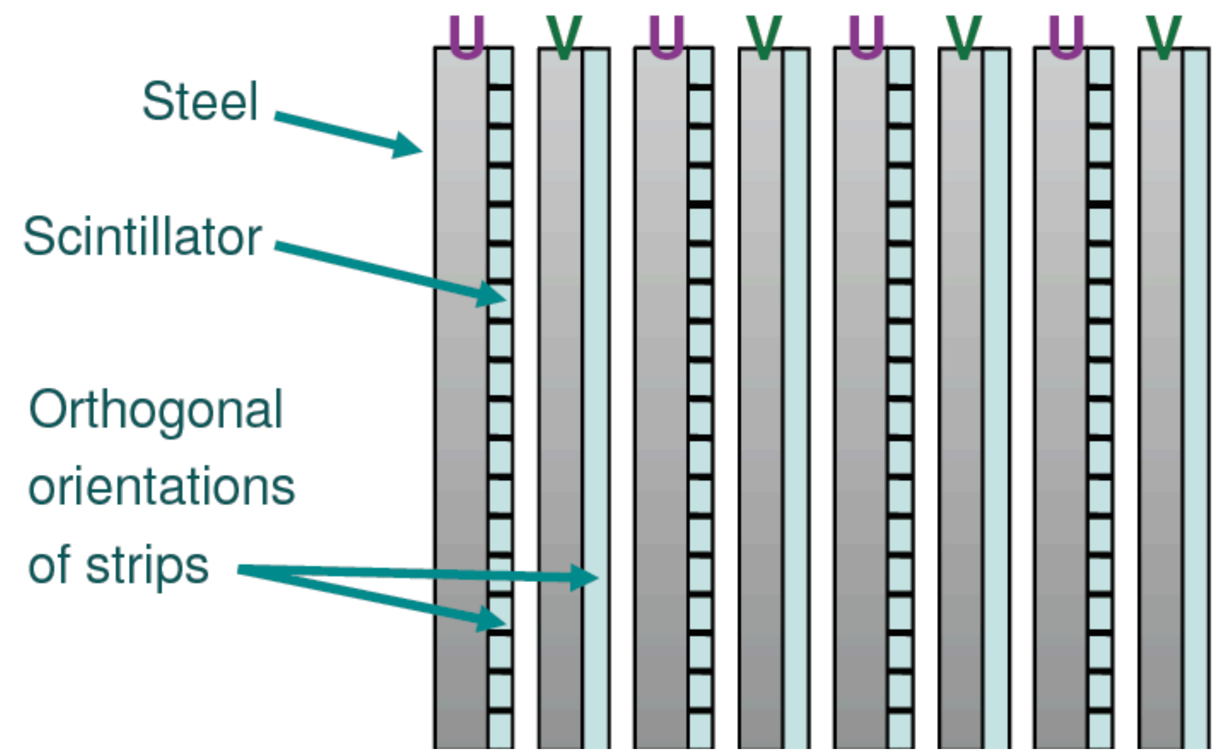


Detectors

Detector Images From http://www-visualmedia.fnal.gov/



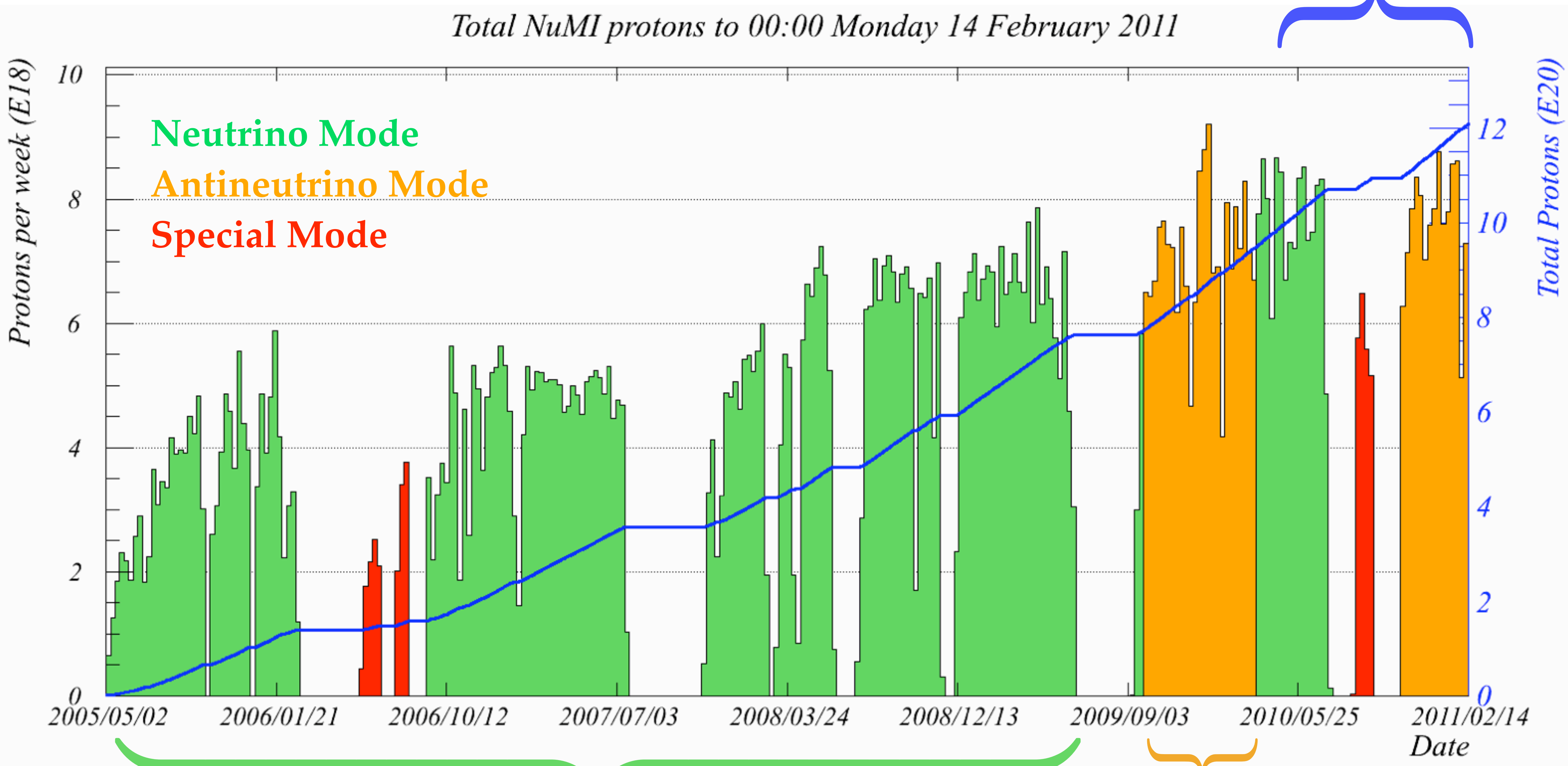




- Functionally Identical Detectors
  - Same iron, scintillator, and magnetic fields
  - Allows cancellation of systematic errors when using both detectors

The Data

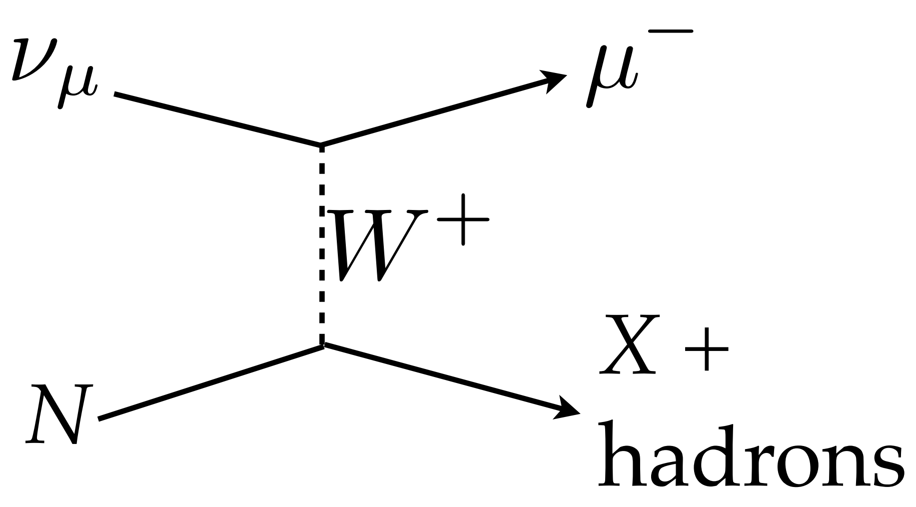
Results Coming Soon



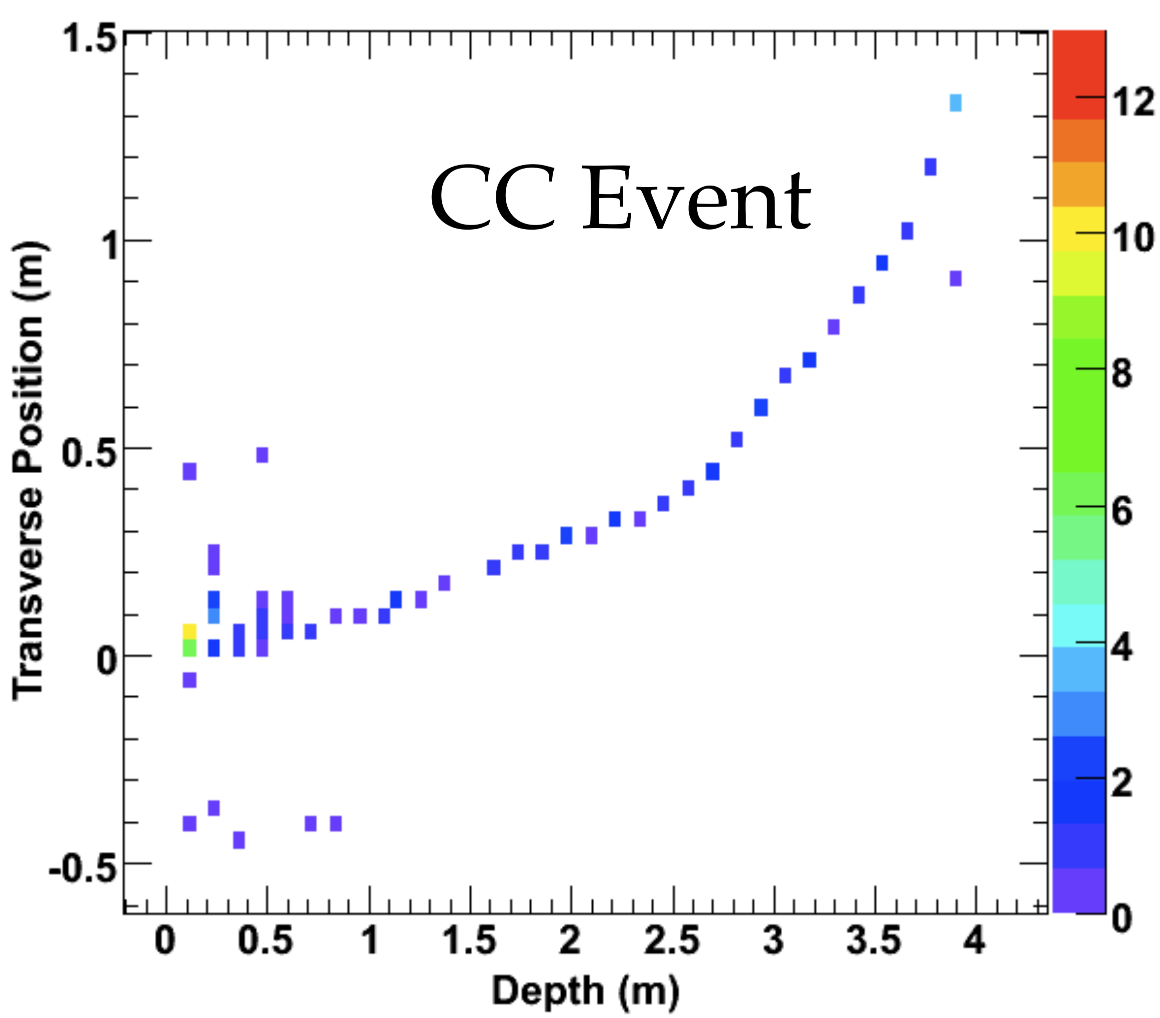
7.0 x 10^{20} POT Neutrino Results

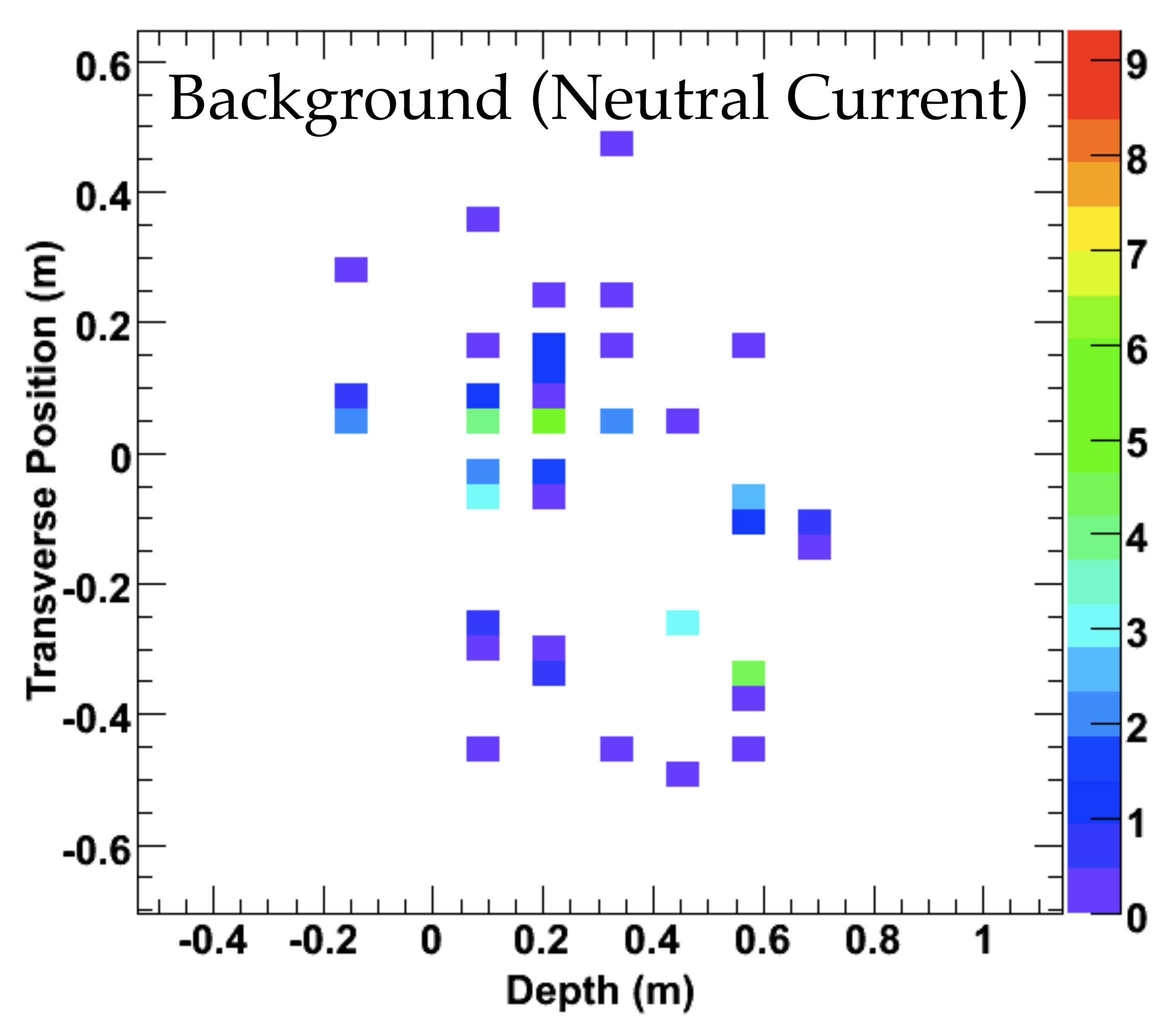
1.7 x 10^{20} POT Neutrino Results

Charged Current Interactions (ν_μ)

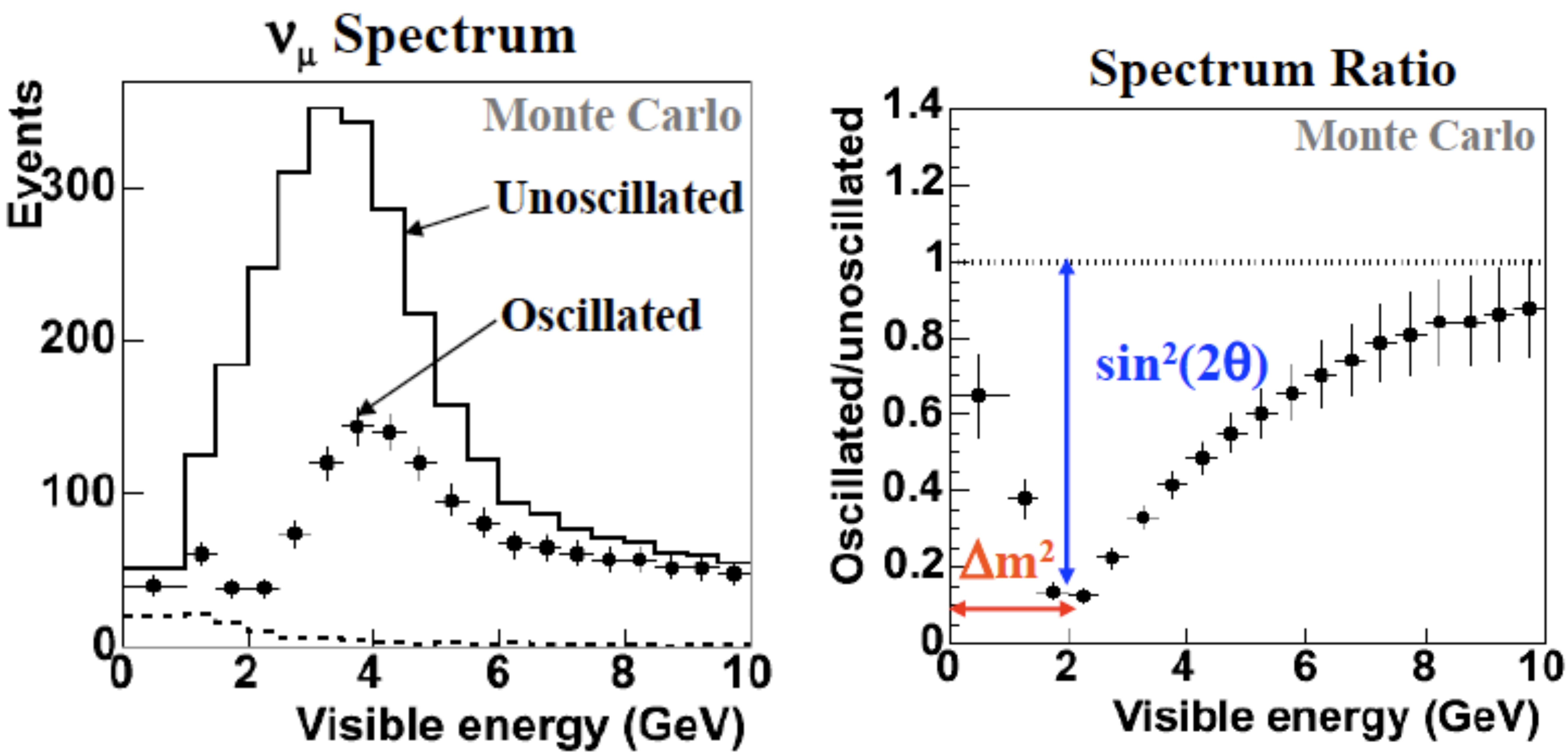


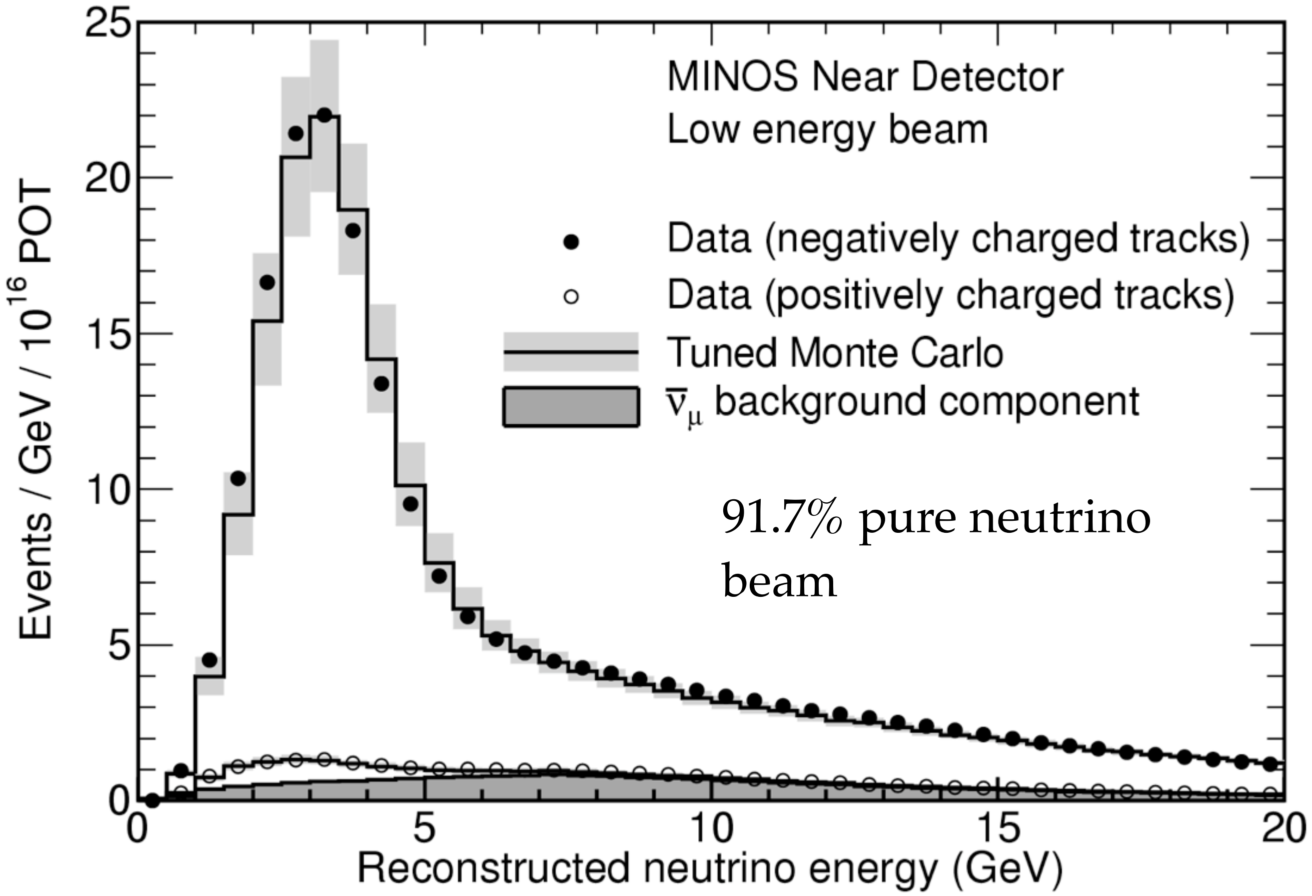
- Oscillations from ν_μ to other types will manifest as a deficit at the far detector

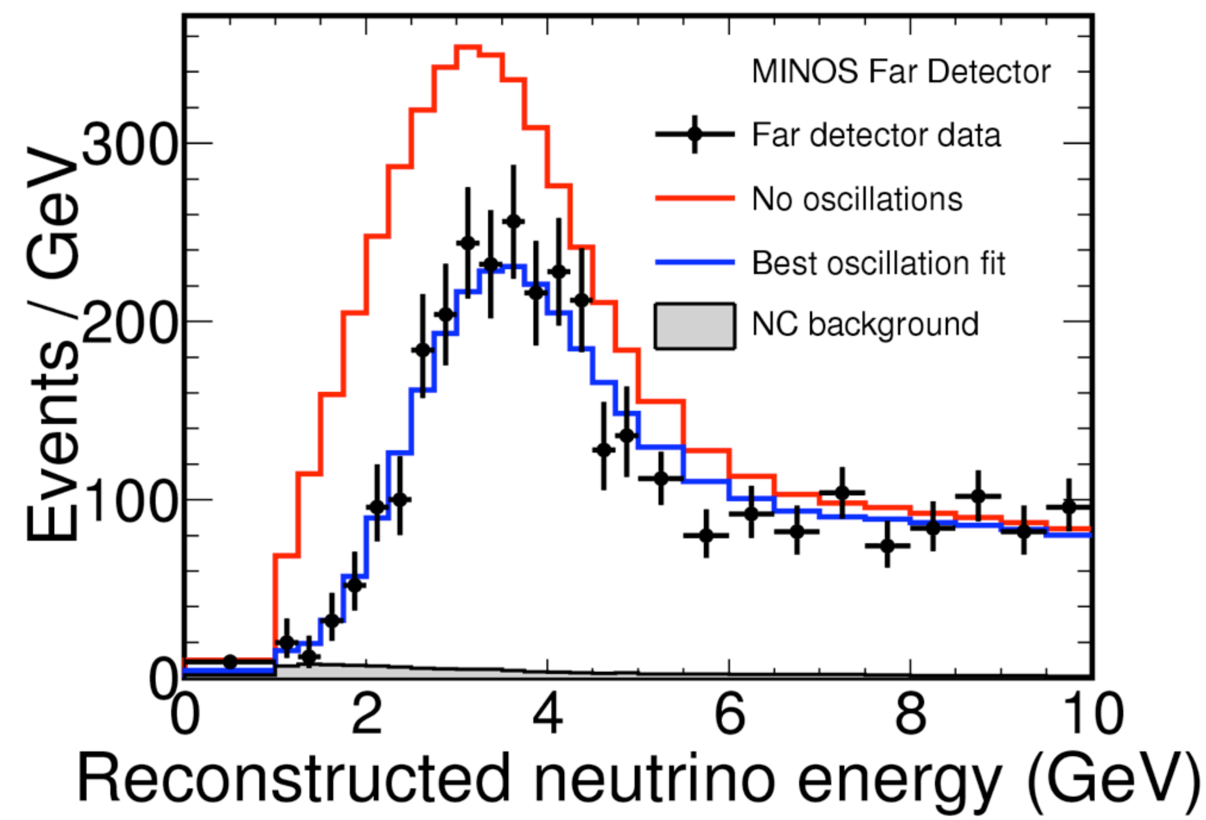


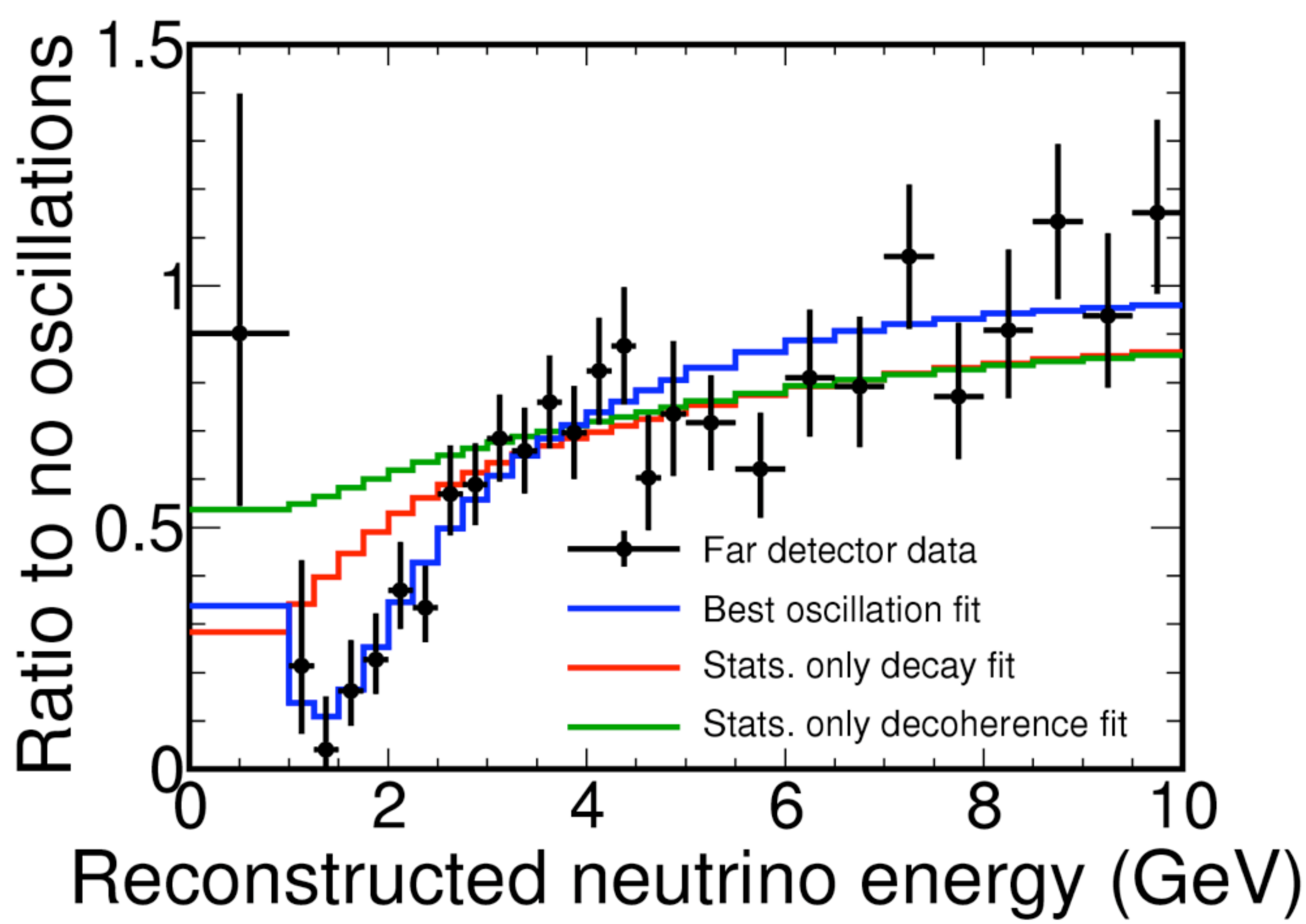


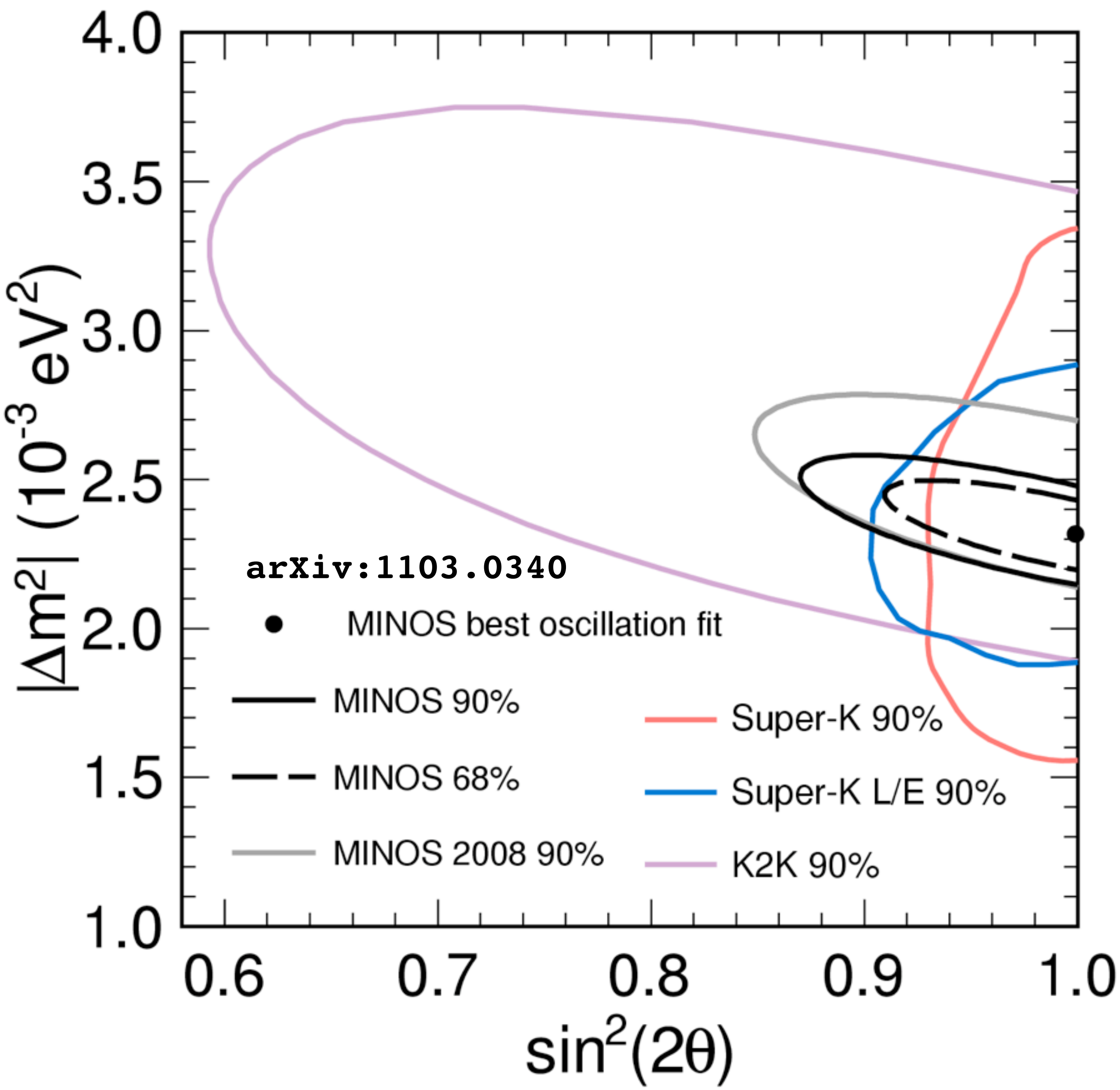
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \boxed{\sin^2(2\theta_{23})} \sin^2\left(\frac{1.27 \times \boxed{\Delta m^2_{32}}/\text{eV} \times L/\text{km}}{E/\text{GeV}}\right)$$




MINOS Near Detector
Low energy beam
Data (negatively charged tracks)
Data (positively charged tracks)
Tuned Monte Carlo
$\bar{\nu}_\mu$ background component
91.7% pure neutrino beam
Events / GeV / 10^{16} POT
Reconstructed neutrino energy (GeV)


MINOS Far Detector
Far detector data
No oscillations
Best oscillation fit
NC background
Events / GeV
Reconstructed neutrino energy (GeV)


Far detector data
Best oscillation fit
Stats. only decay fit
Stats. only decoherence fit
Ratio to no oscillations
Reconstructed neutrino energy (GeV)

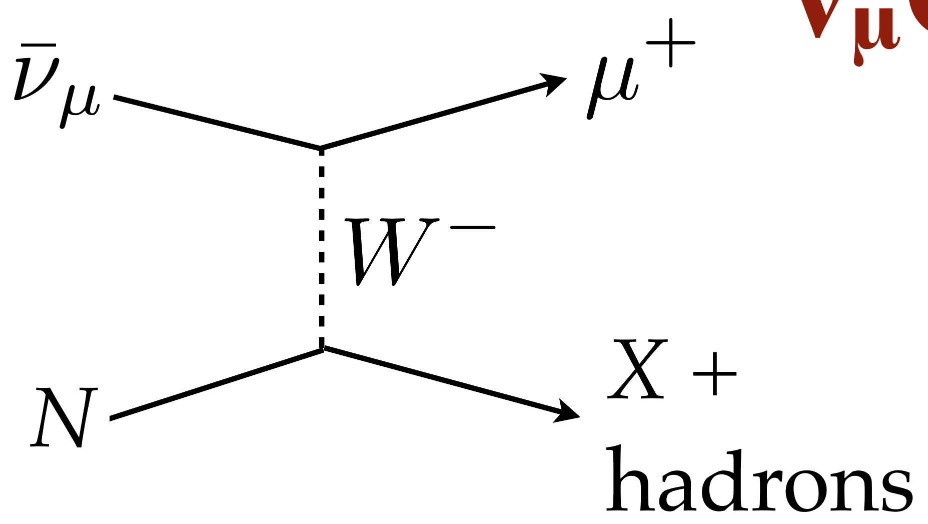


$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \mathrm{eV}^2$$

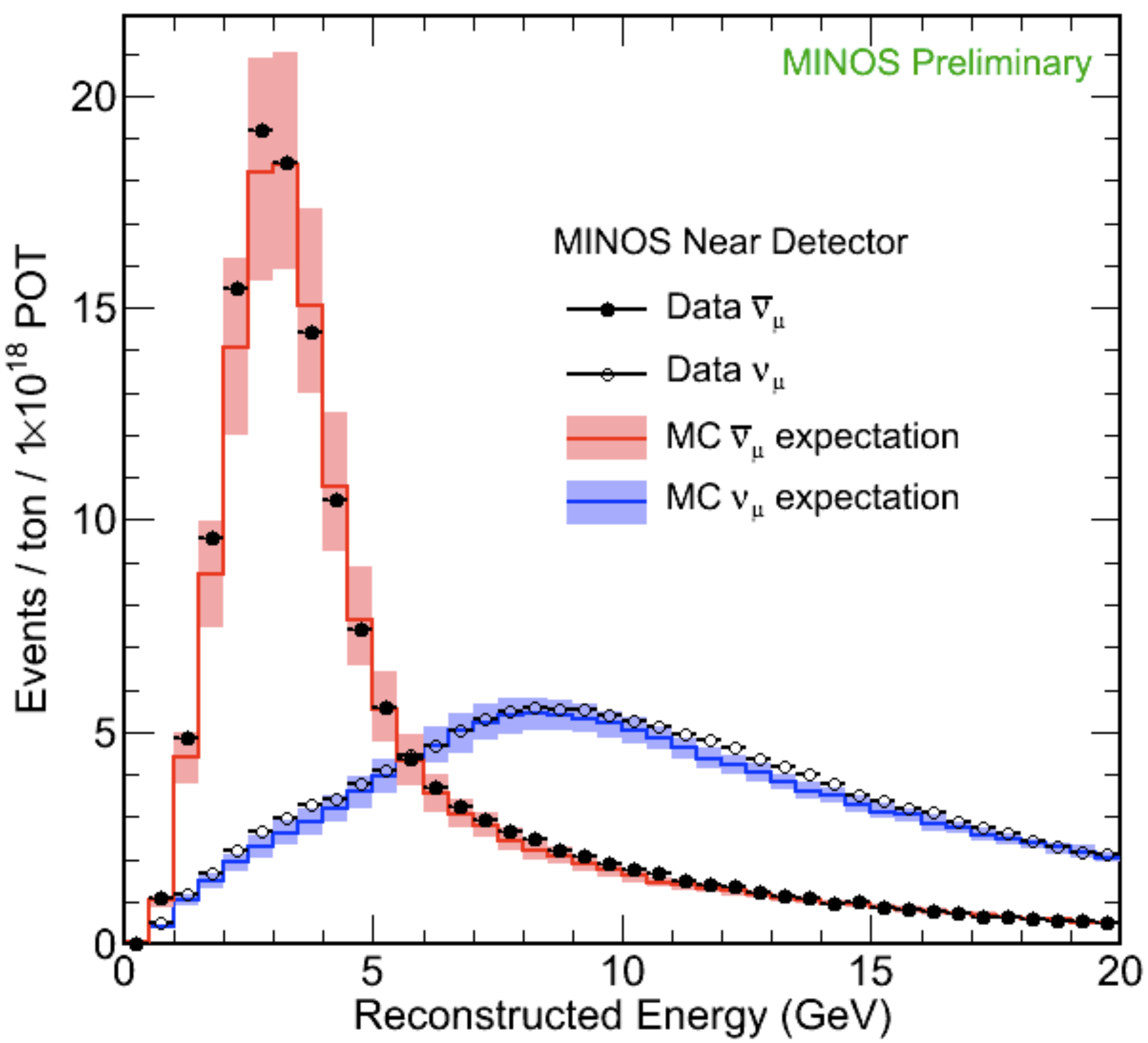
$$\sin^2(2\theta) > 0.90 (90\%\ C.L.)$$

- Pure decoherence disfavored at 9σ
- Pure decay at 7σ
- World's most precise $|\Delta m^2|$ measurement
- Included Samples
  - Fiducial Events
  - Events outside fiducial volume
  - Muons from neutrino events in rock

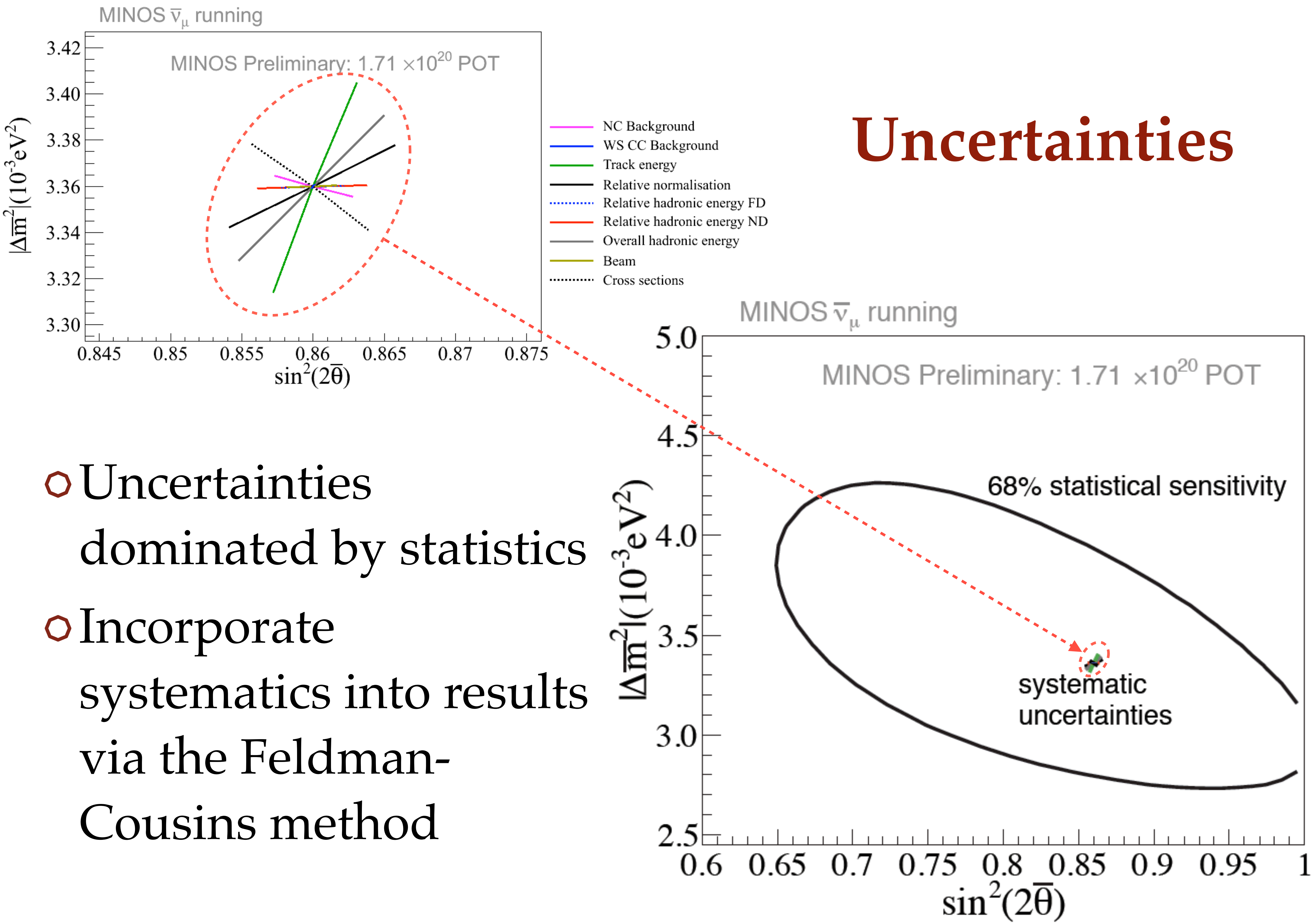
$\bar{\nu}_\mu$ Charged Current



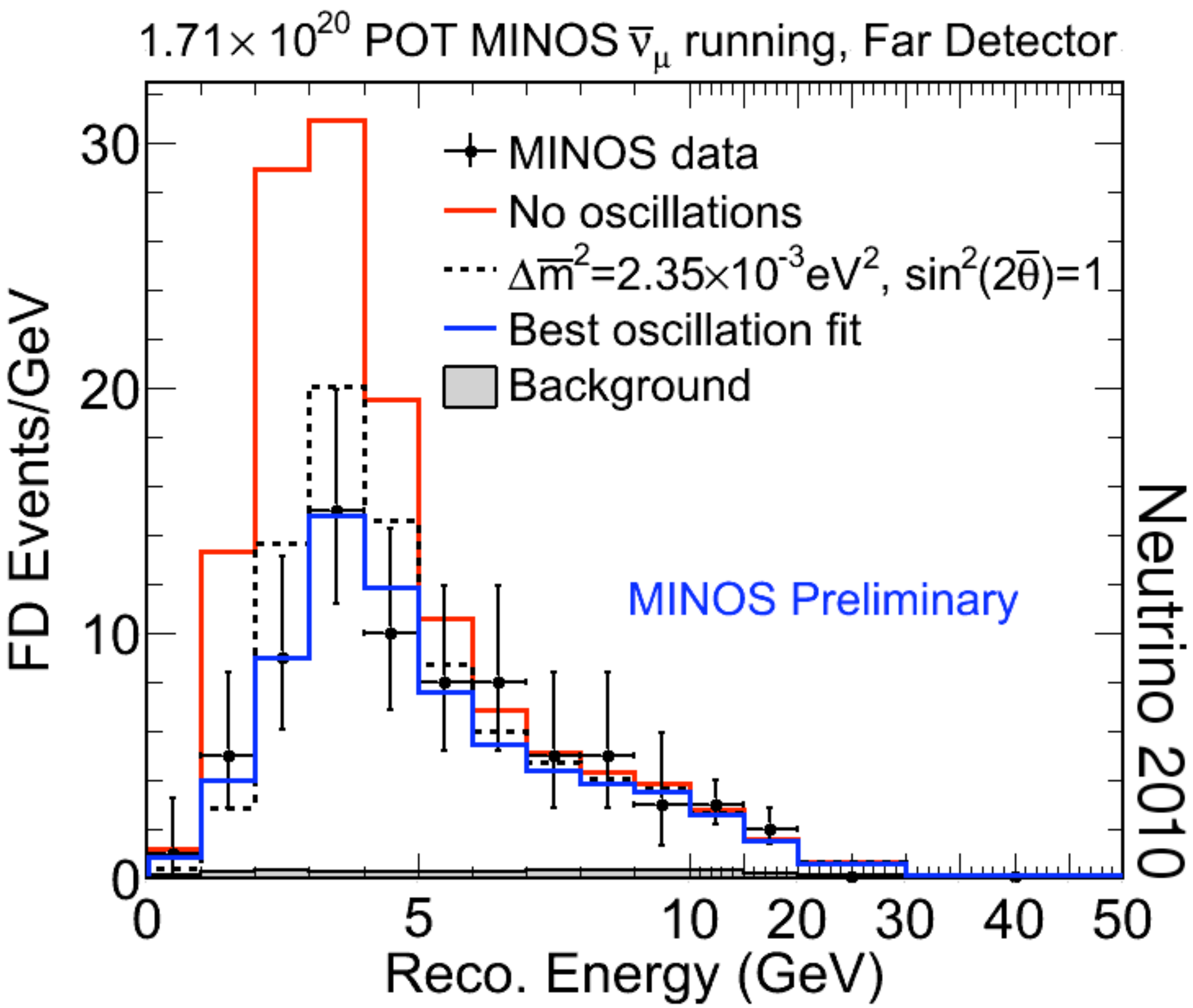
- Similar to ν_μ analysis but with reversed horn current.
- Background
  - Neutral Current events (low energies)
  - Wrong sign CC events
- To reject wrong signs select events with positive reconstructed charge
- 39.9% pure antineutrino beam

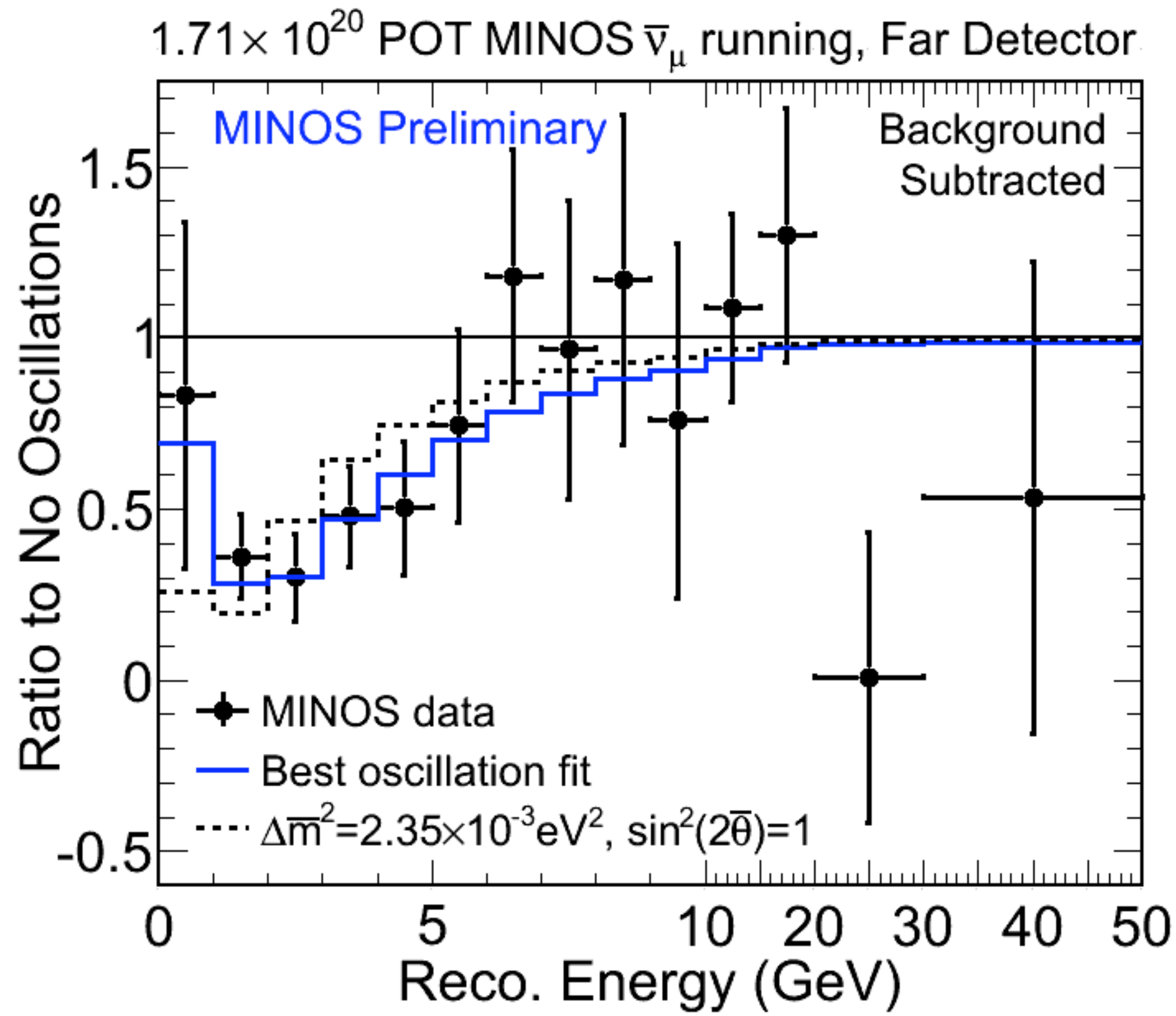


Uncertainties



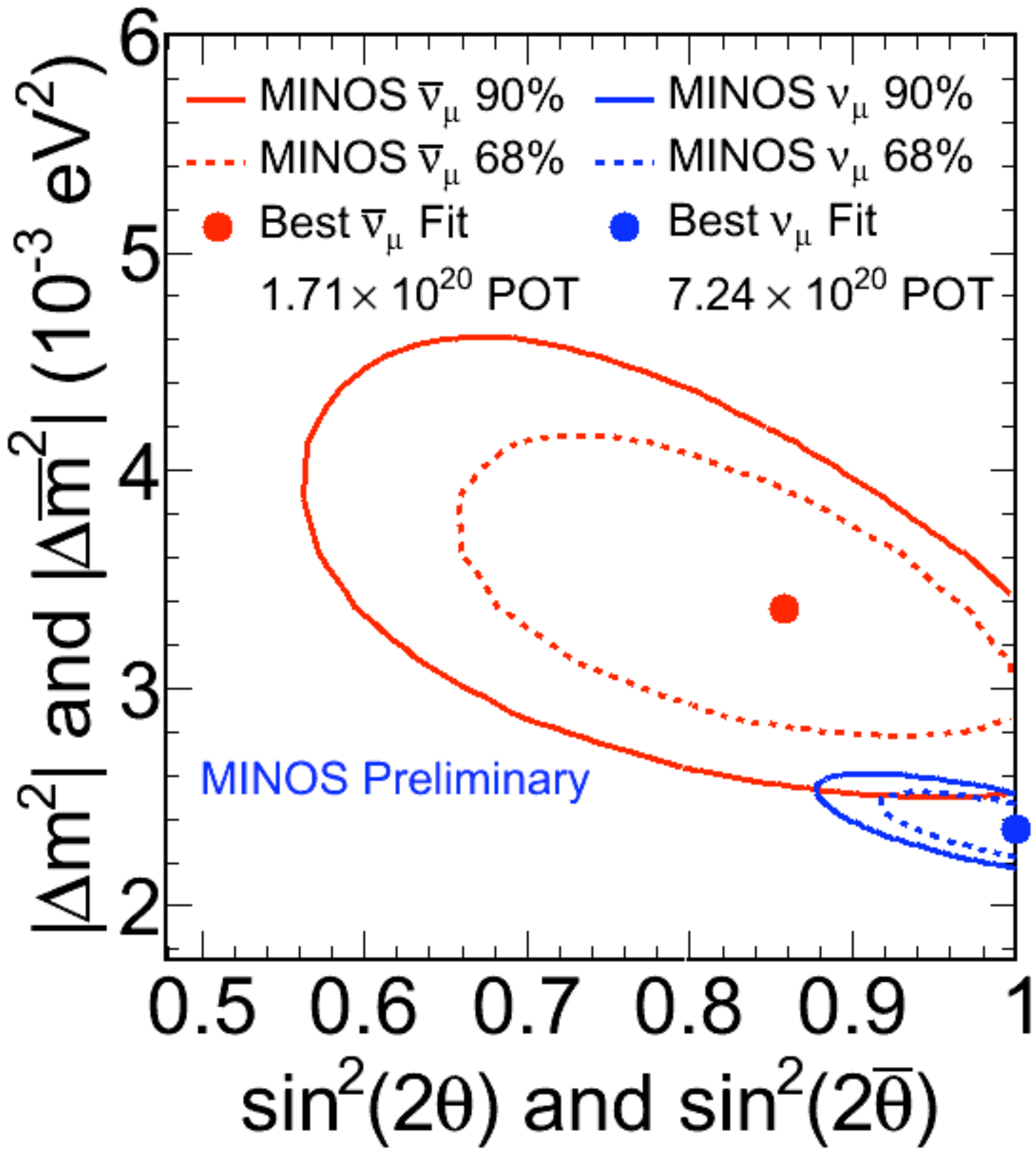
- Uncertainties dominated by statistics
- Incorporate systematics into results via the Feldman-Cousins method





$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

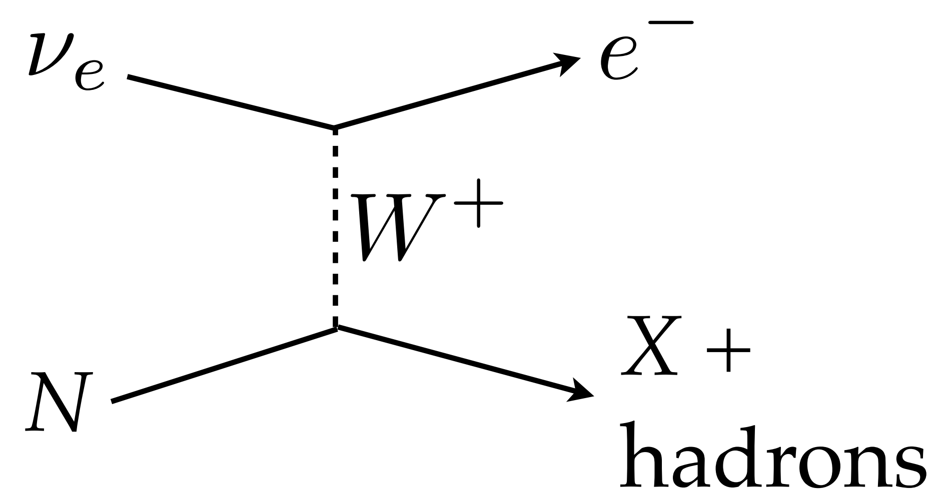
$$|\Delta\bar{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\mathrm{eV}^2$$



- Interesting Tension (2.3σ difference)
- Plan to have at least double current data set by this Summer.
  - Data taking interrupted by target failure on Feb. 26
  - Plan to have new target in April

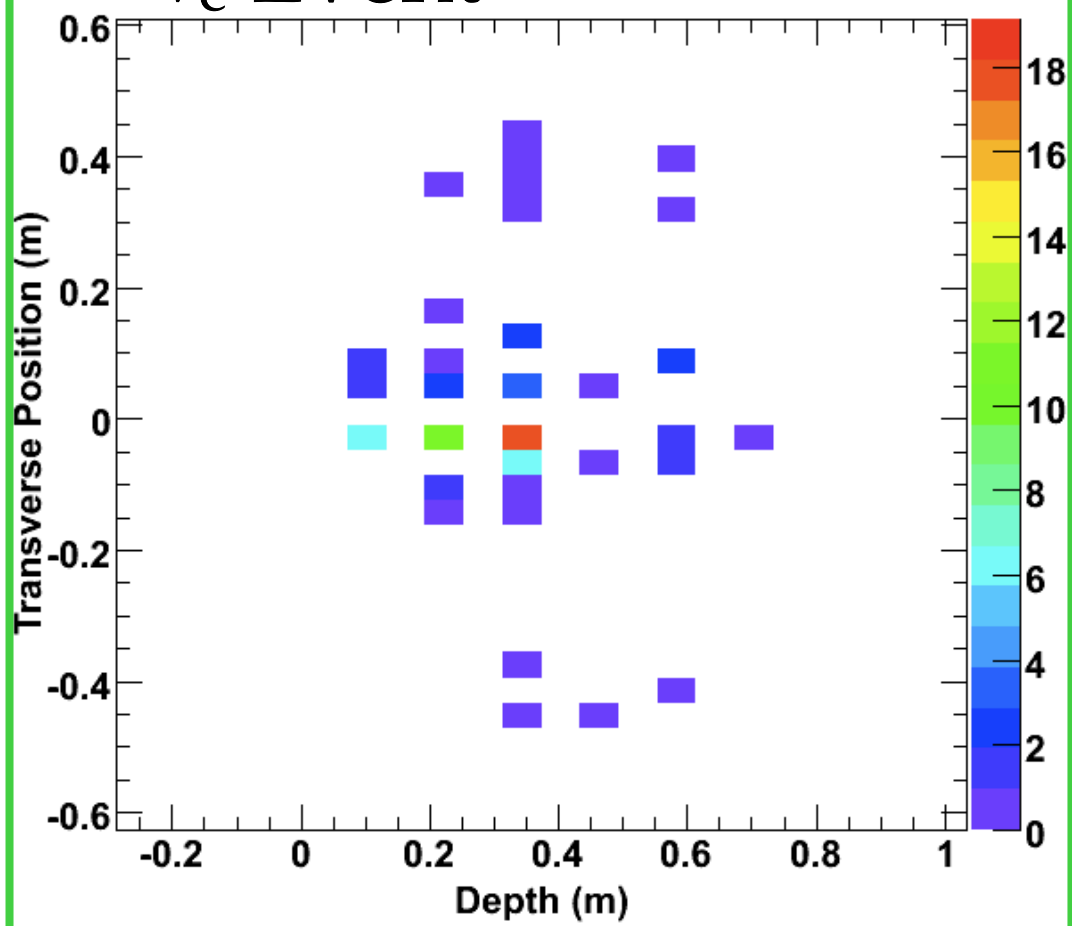
ν_e Appearance

- Very challenging
- Neural Network separates signal and BG



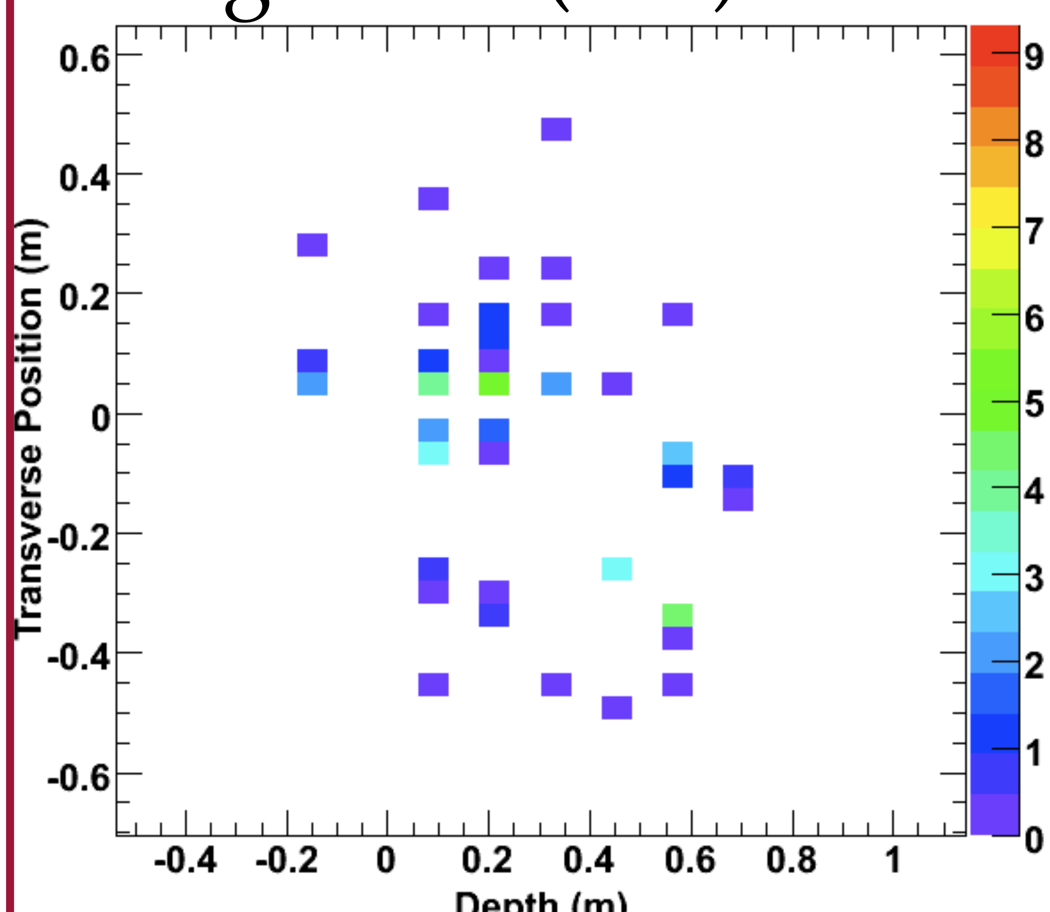
$$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(\frac{1.27 \times \Delta m^2_{32}/\mathrm{eV}^2 \times L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$

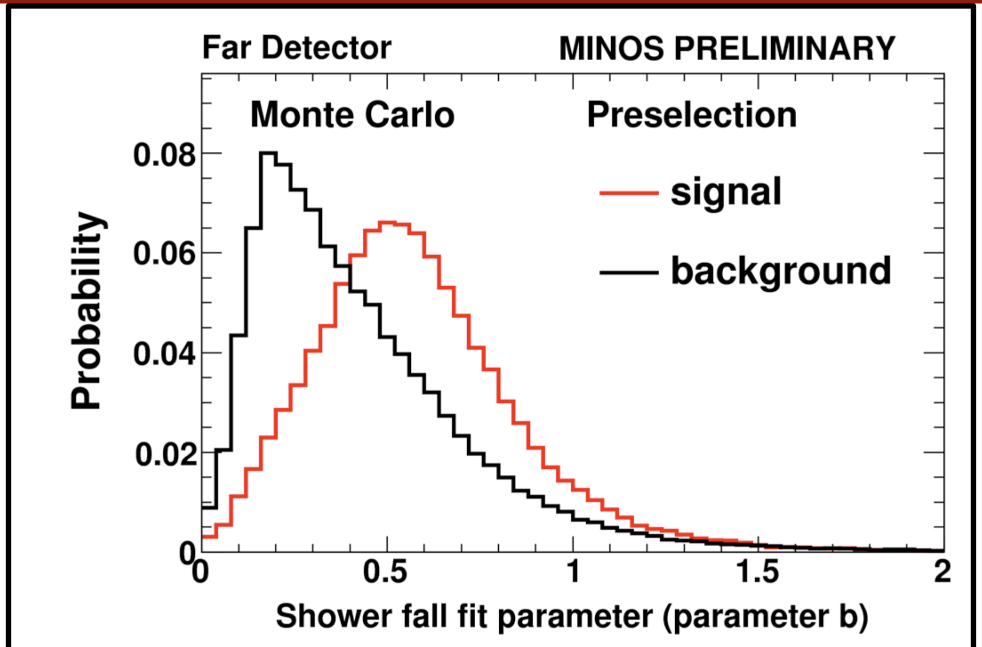
ν_e Event

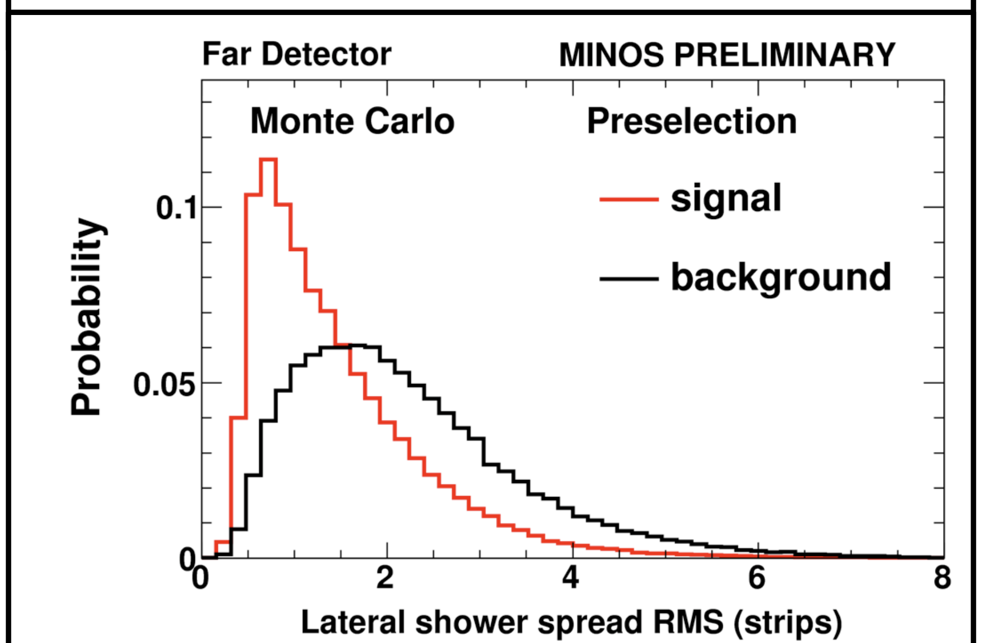


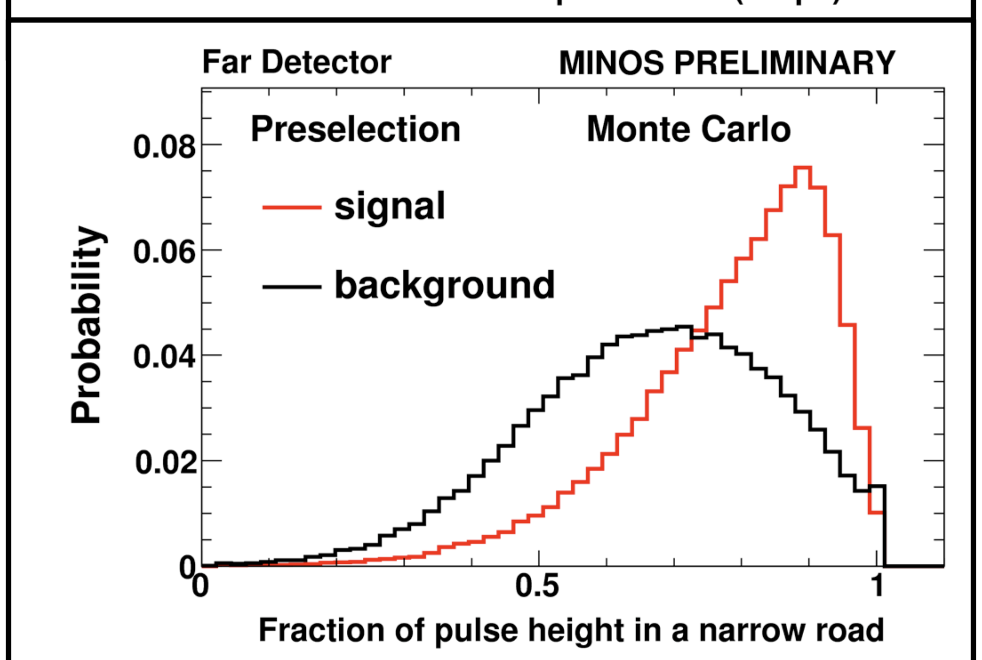
Only Unmeasured PMNS angle

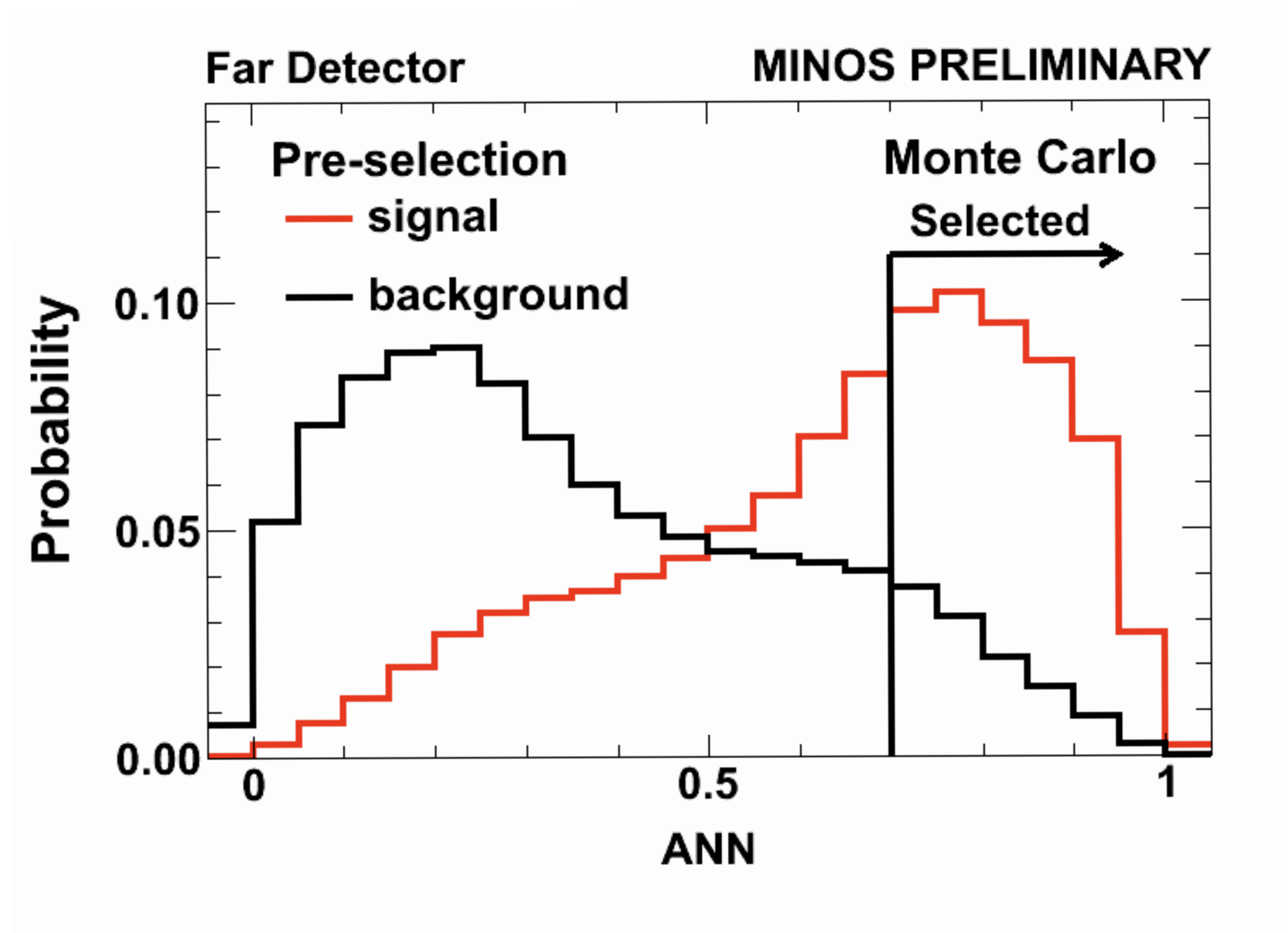
Background (NC) Event



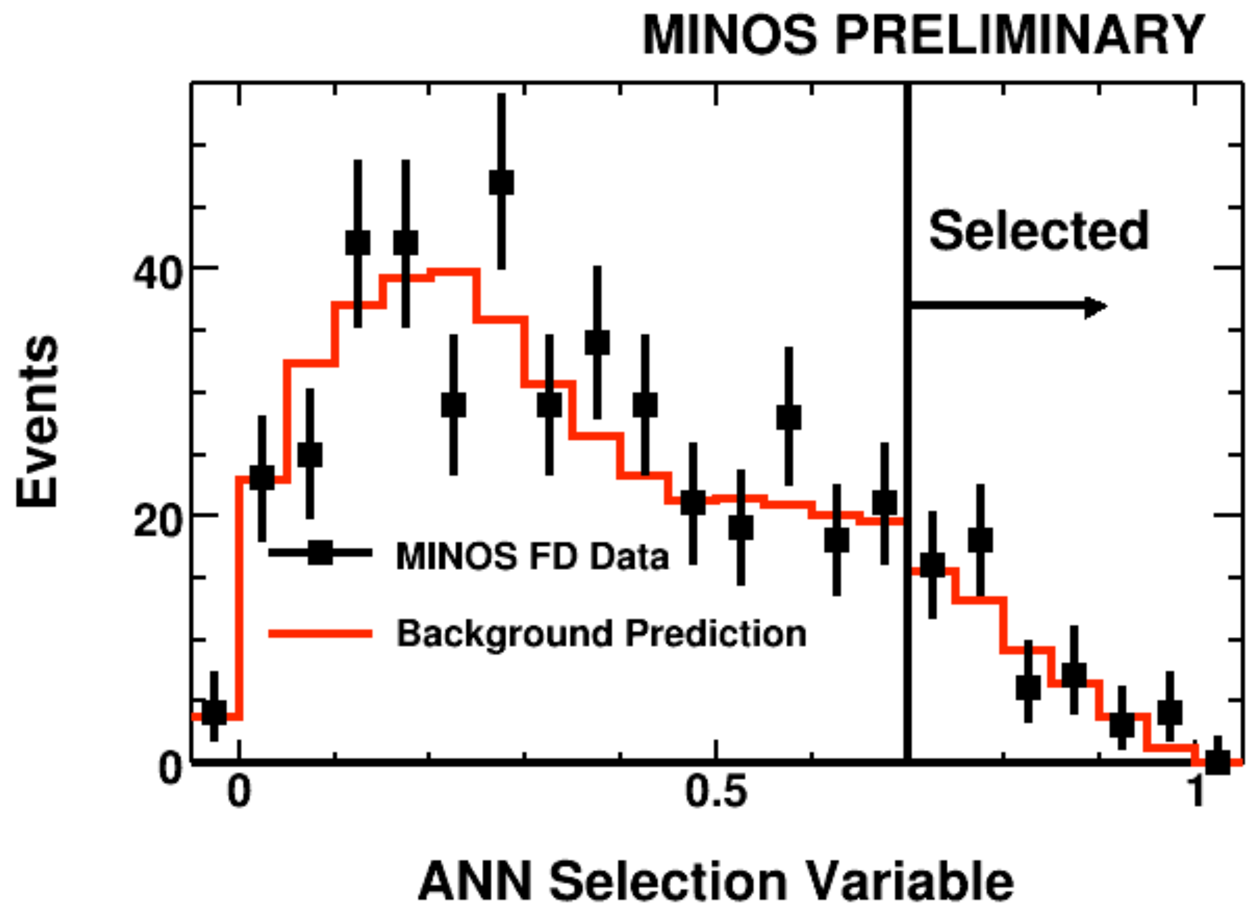


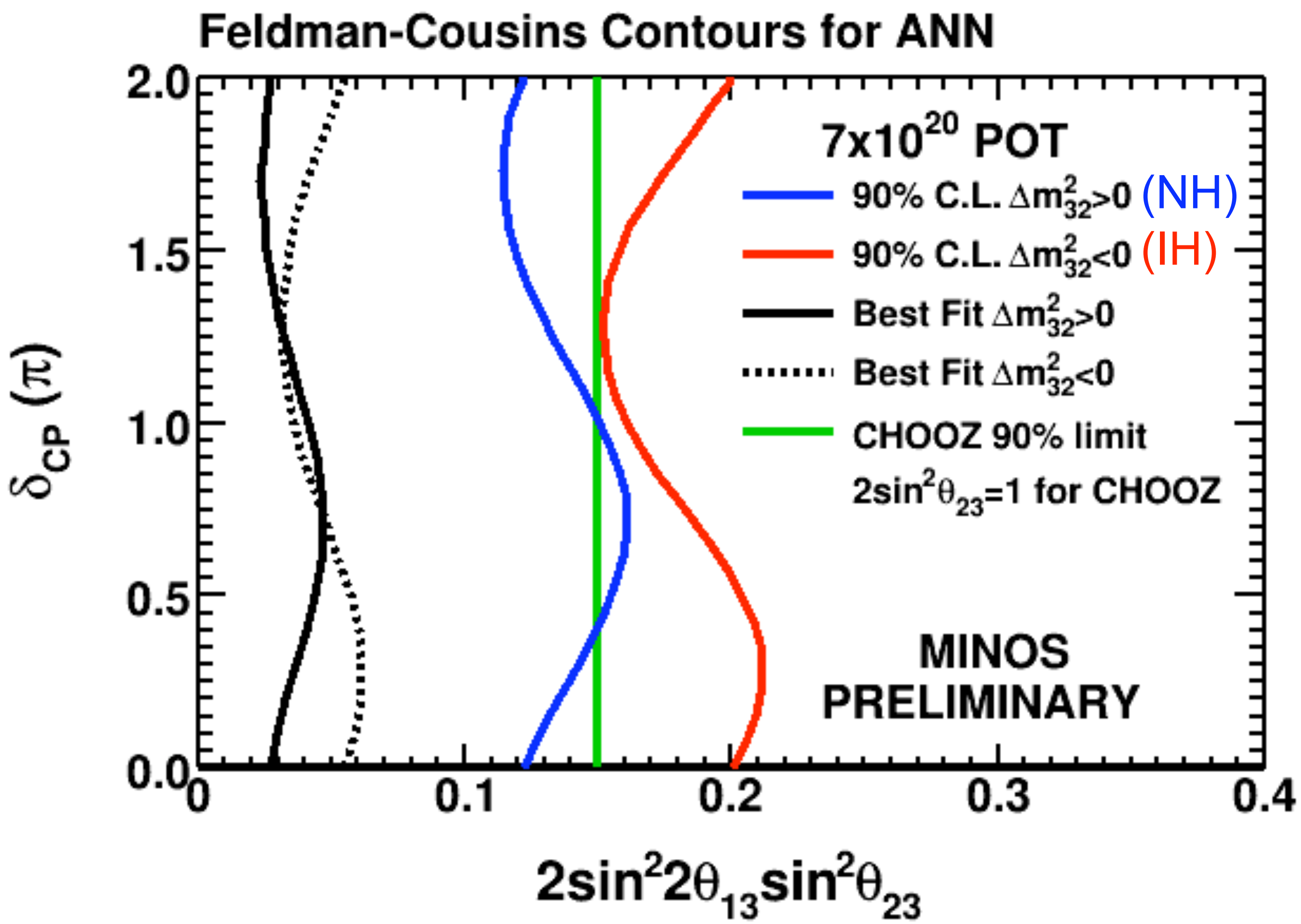






- ANN uses 11 variables
- Most important plotted
- Select ANN > 0.7





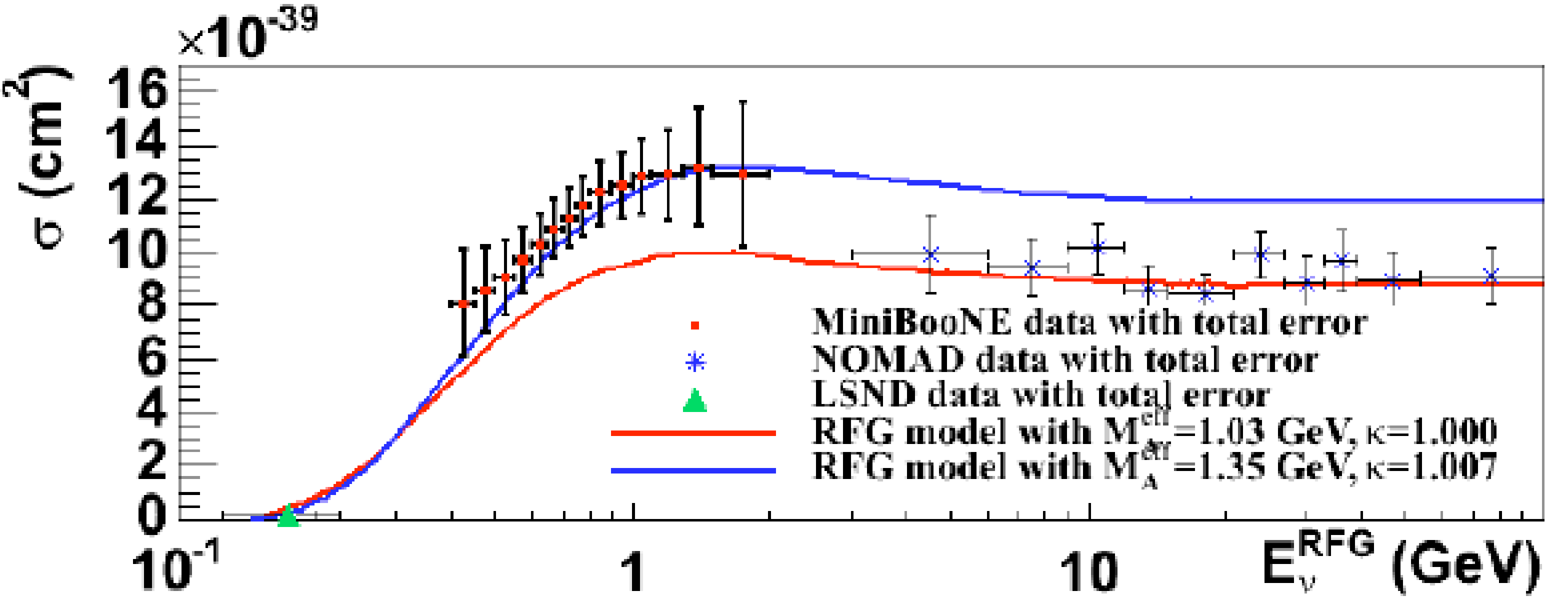
Assuming $\theta_{23} = \pi/4,\ \delta_{\rm CP} = 0,\ |\Delta m^2_{32}| = 2.43 \times 10^{-3}$

Normal Hierarchy : $\sin^2(2\theta_{13}) < 0.12\ (90\%\mathrm{C.L.})$

Inverted Hierarchy : $\sin^2(2\theta_{13}) < 0.20\ (90\%\mathrm{C.L.})$

- Better than CHOOZ limit for most of NH
- More data collected
- Multiple analysis improvements underway

Quasi-Elastic Scattering



Known from neutron beta decay measurements

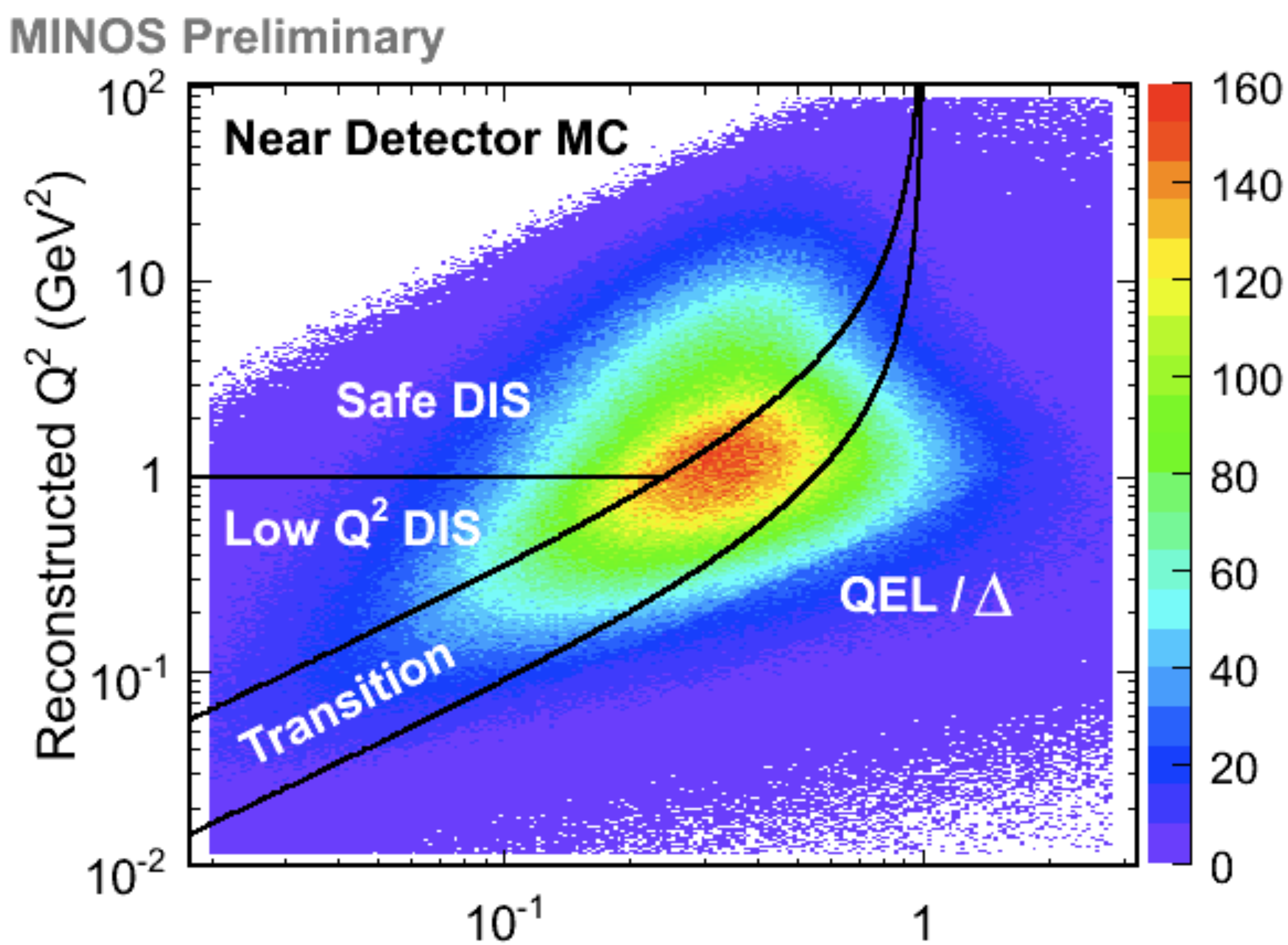
$$F_A(q^2) = \frac{F_A(0)}{(1 - q^2/M_A^2)^2}$$

Energy transferred in interaction

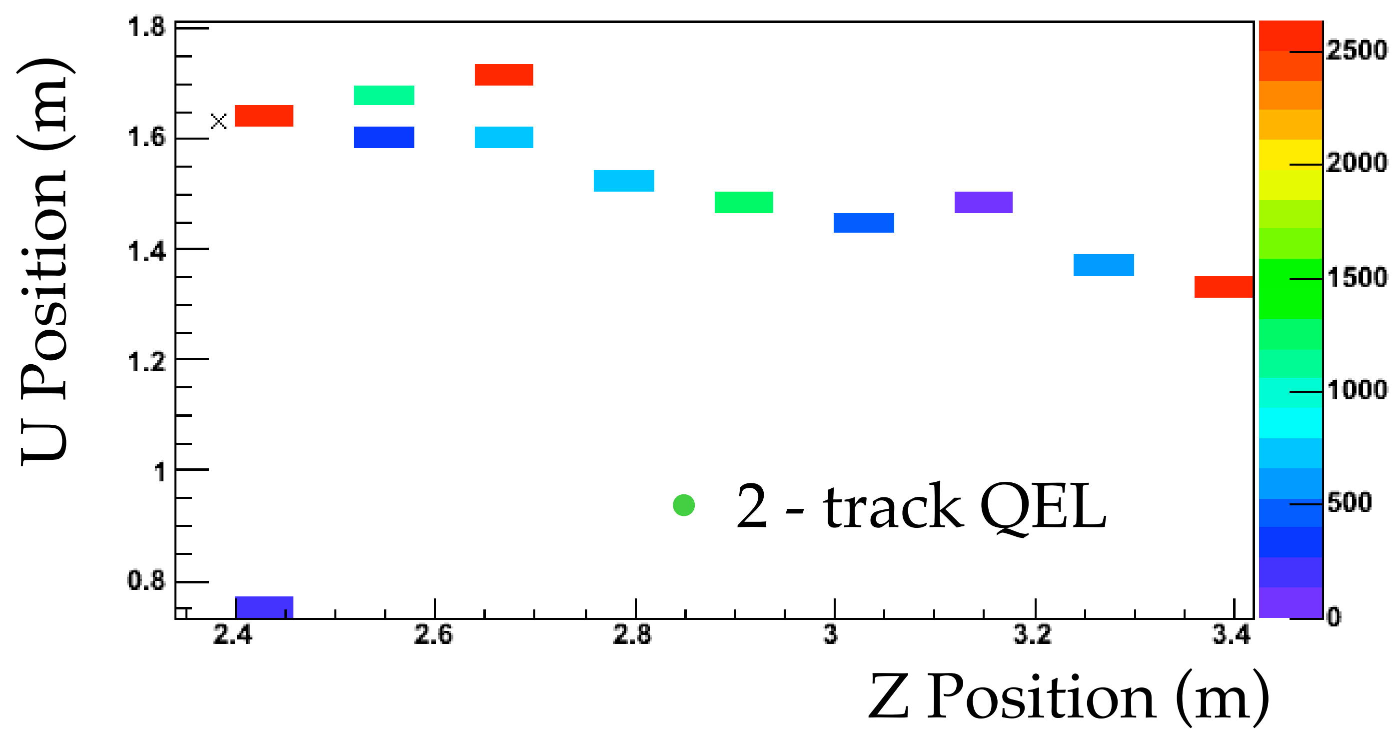
- Use ν's as probe to measure axial vector mass M_A
- Internal nuclear structure and interactions are very difficult to model
- MINOS can address gap between MiniBooNE and NOMAD

Complementary Samples

- We can compare how well different parts of our model are simulating the data.
  - 1 - track QEL
  - 2 - track QEL
  - 2 - track resonance like

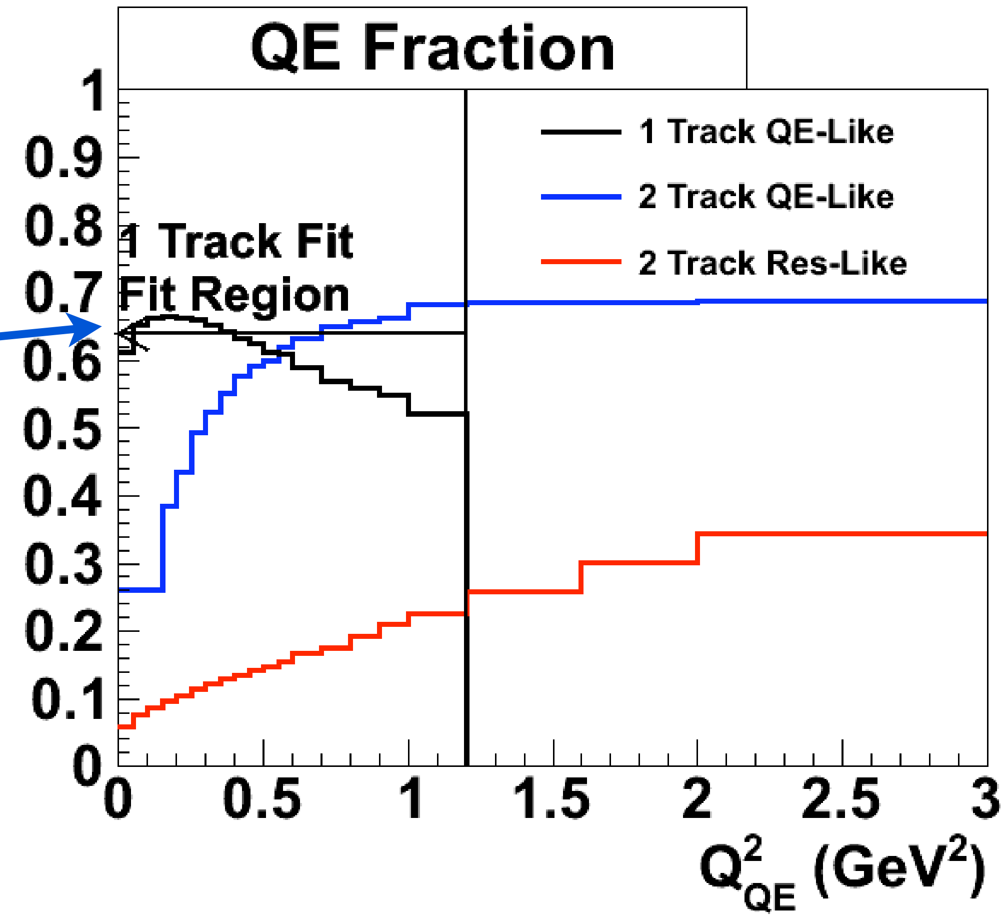


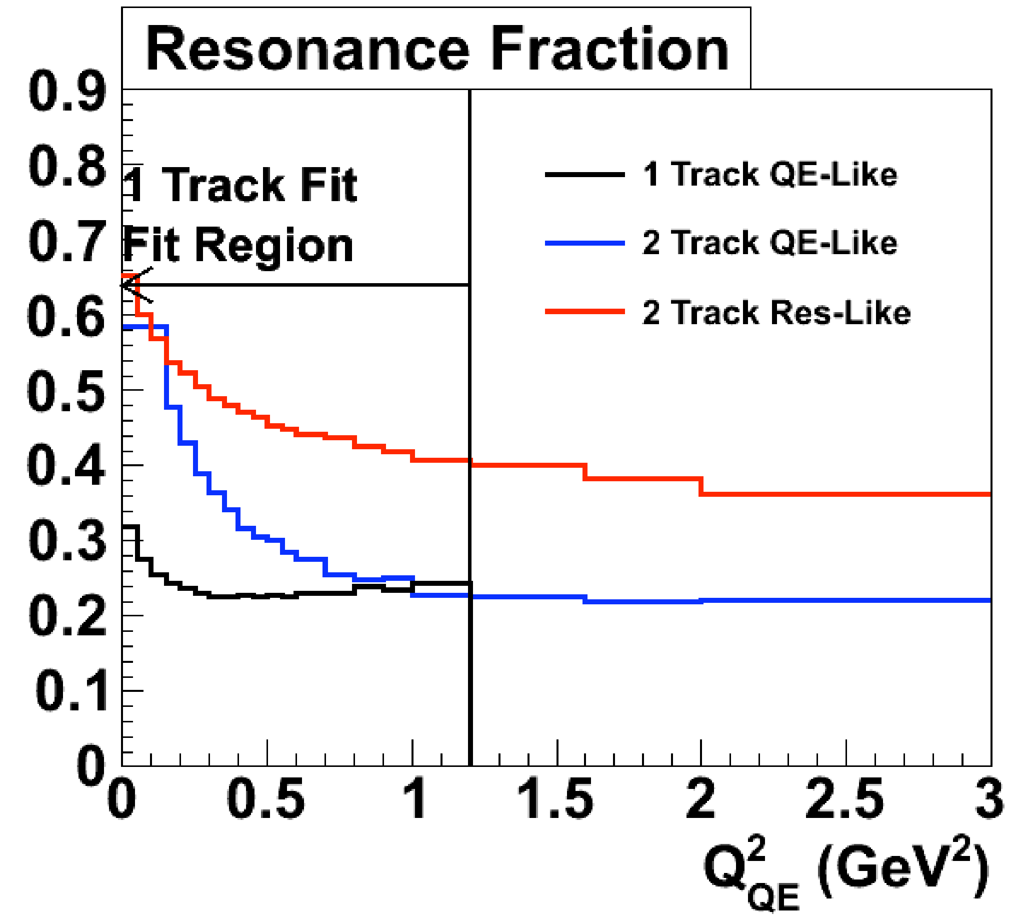
$$x = \frac{Q^2}{2}\vec{p}_N \cdot (\vec{p}_\mu - \vec{p}_\nu)$$



Sample Purity

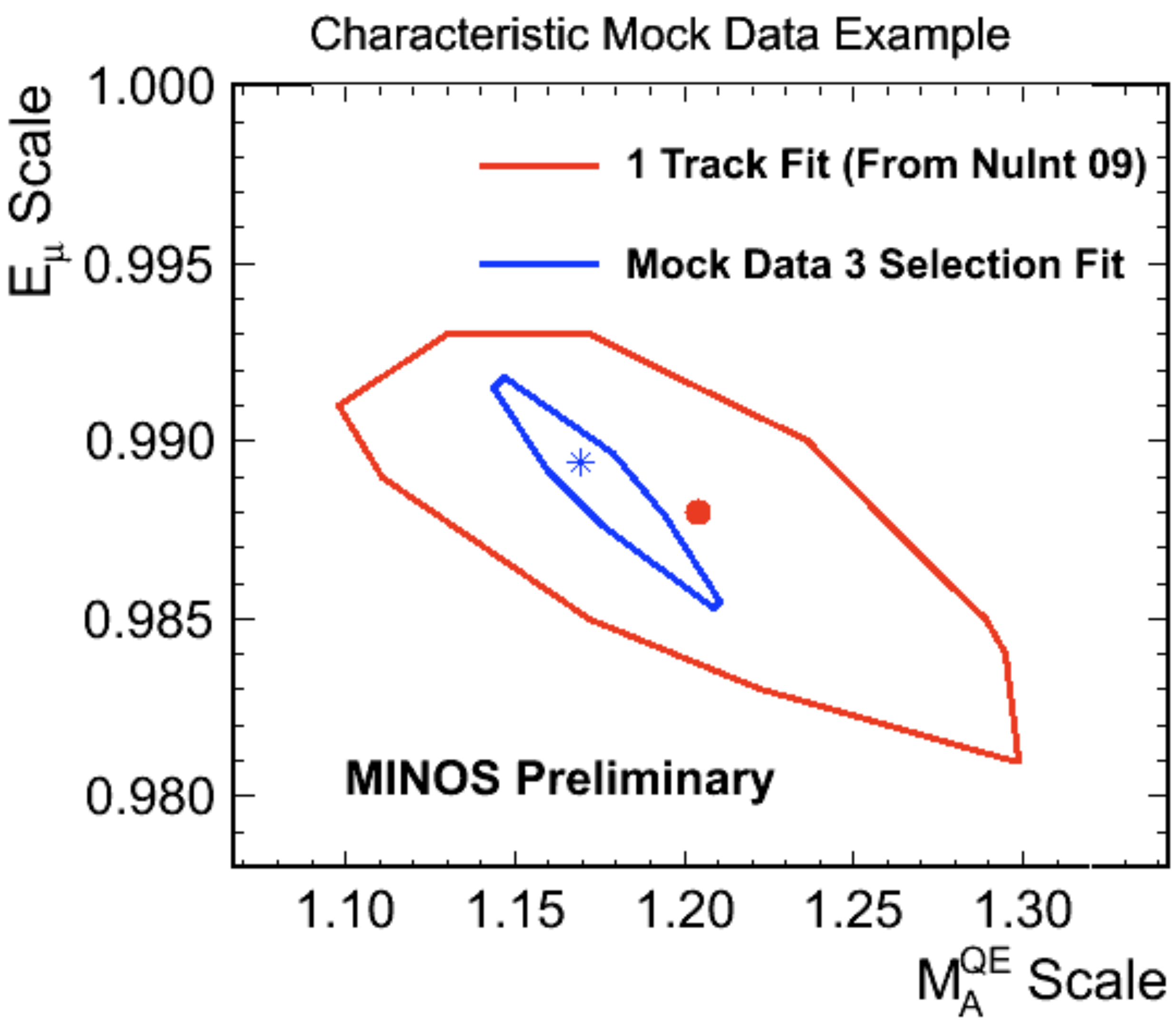
The two QE-like selections keep a nearly constant 65-70% purity across the entire Q^2 spectrum.

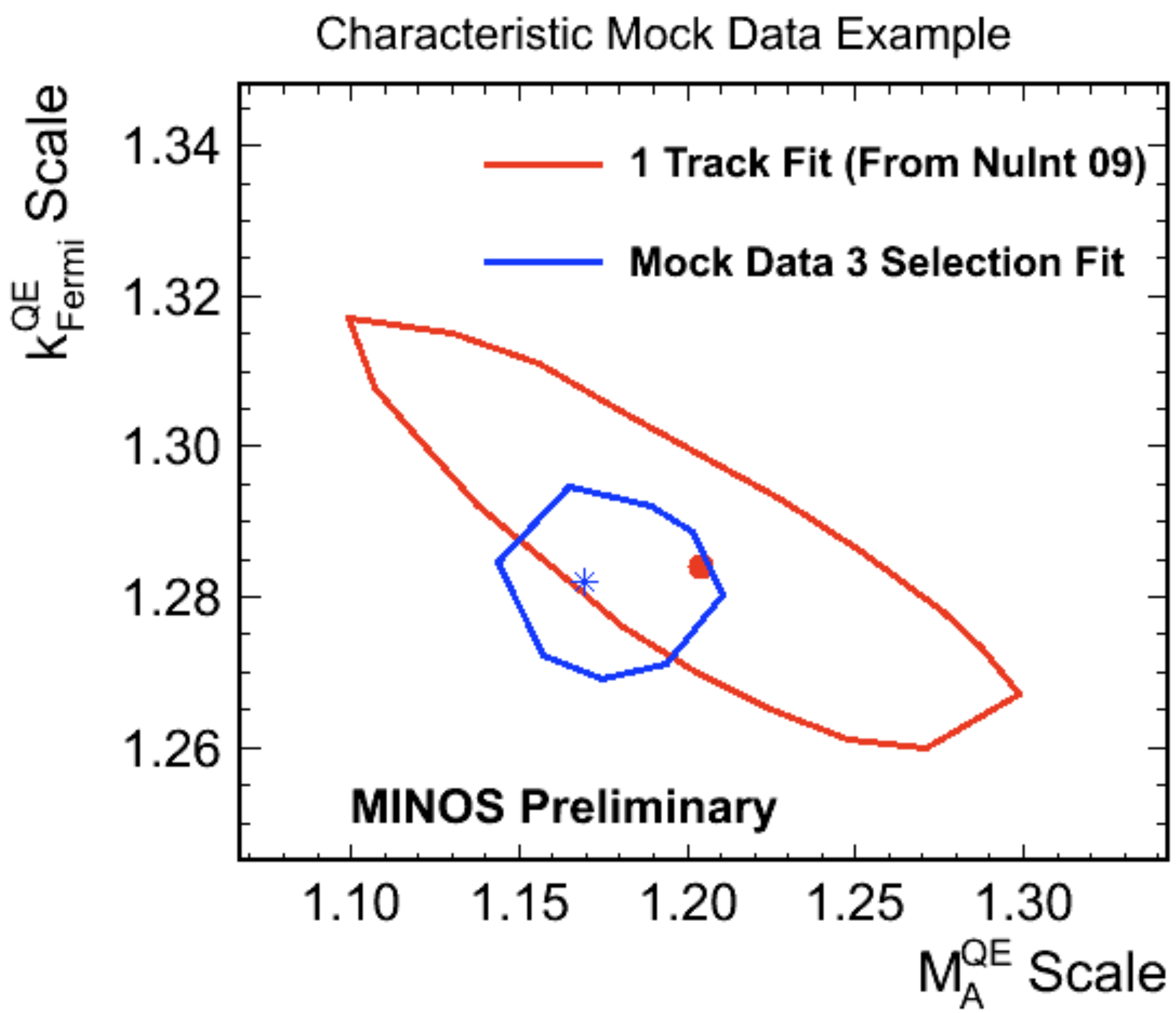




- The 2 track QE sample has its highest purity where the 1 track QE sample is falling off.
- We can use this as a handle on the low Q^2 region
- We can break correlation between the k_{Fermi} and M_A^{QE}

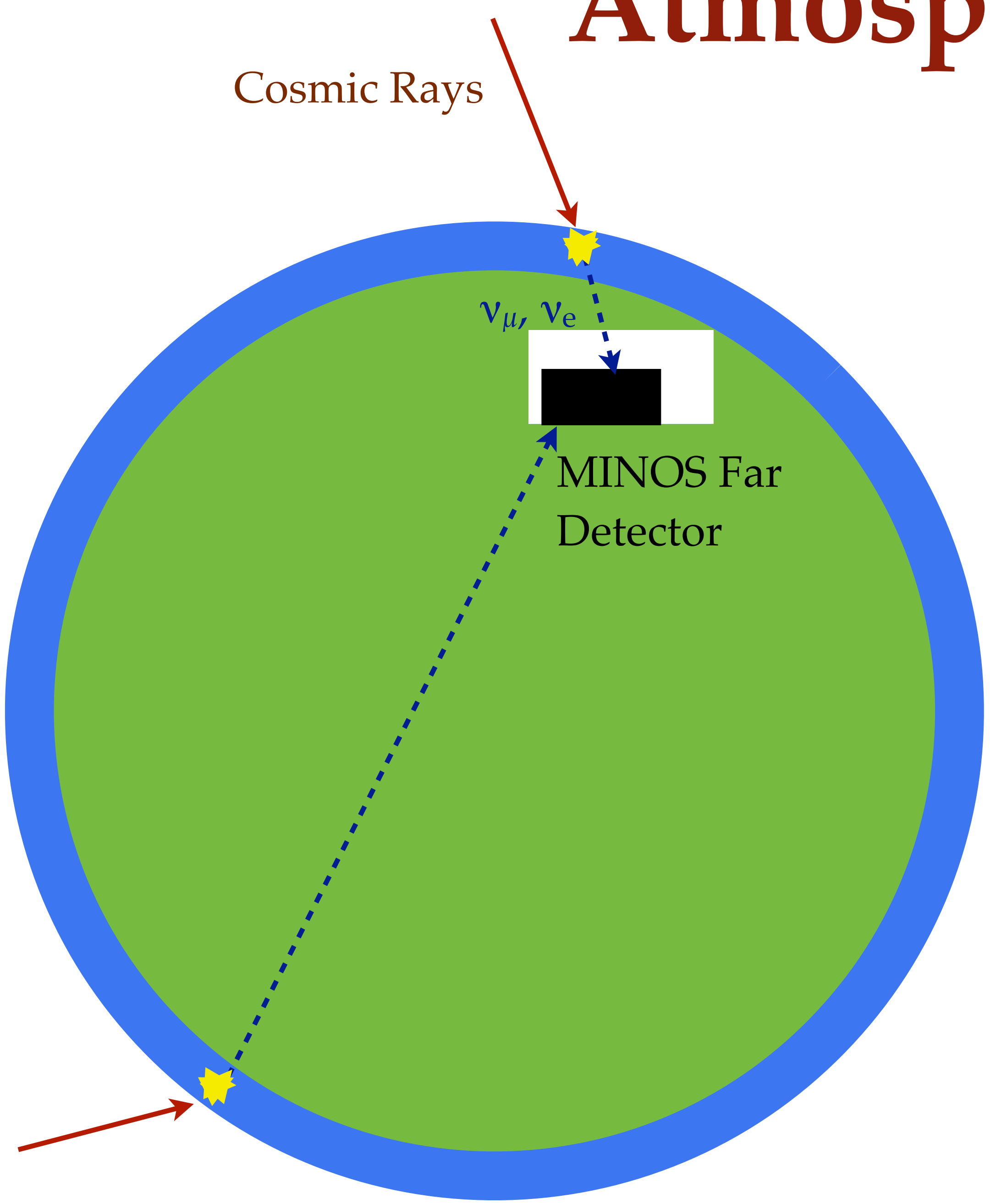
Projected Sensitivity Contours





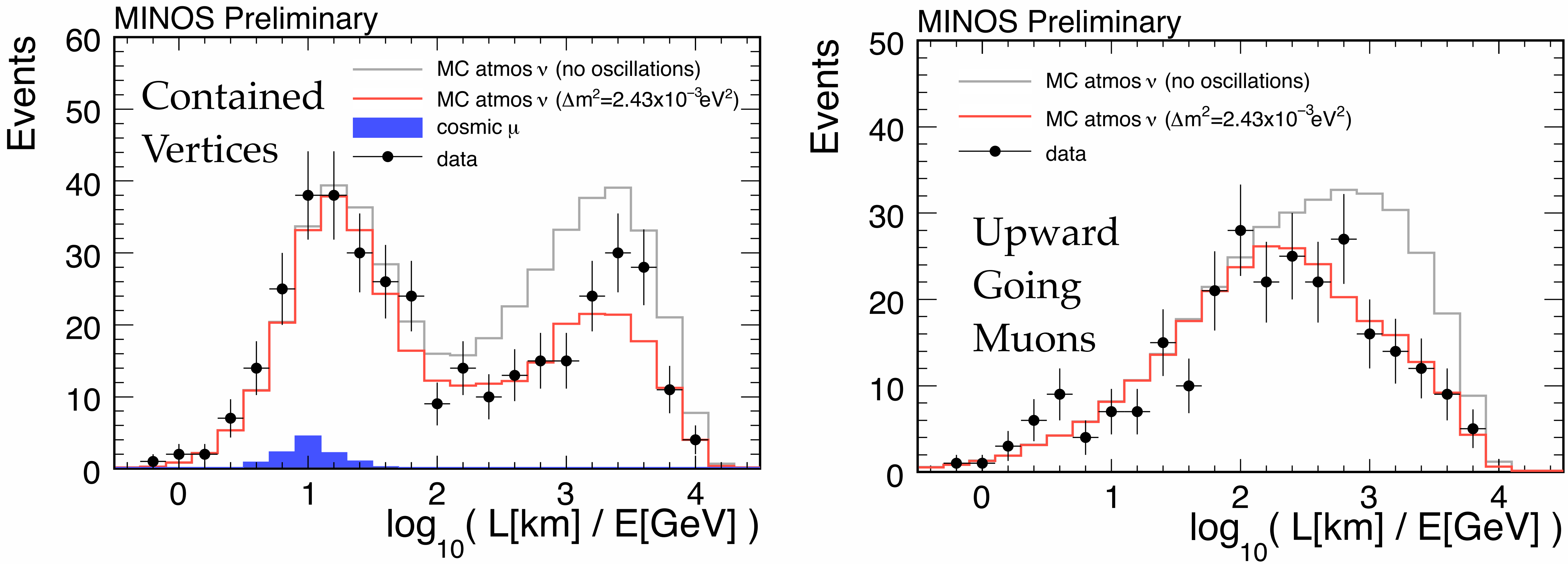
- Assuming central value remains unchanged
  - Previous measurement: $M_A^{QE} = 1.19^{+0.09+0.12}_{-0.10-0.14}$
  - Projected Sensitivity: $M_A^{QE} = 1.19^{+0.03+0.12}_{-0.04-0.14}$

Atmospheric Neutrinos



- Far Detector can detect neutrinos from cosmic ray interactions
- L varies from ~10 to ~13000 km
- L/E spans 4 orders of magnitude
- Oscillations in ν_μ and $\bar{\nu}_\mu$ are detected

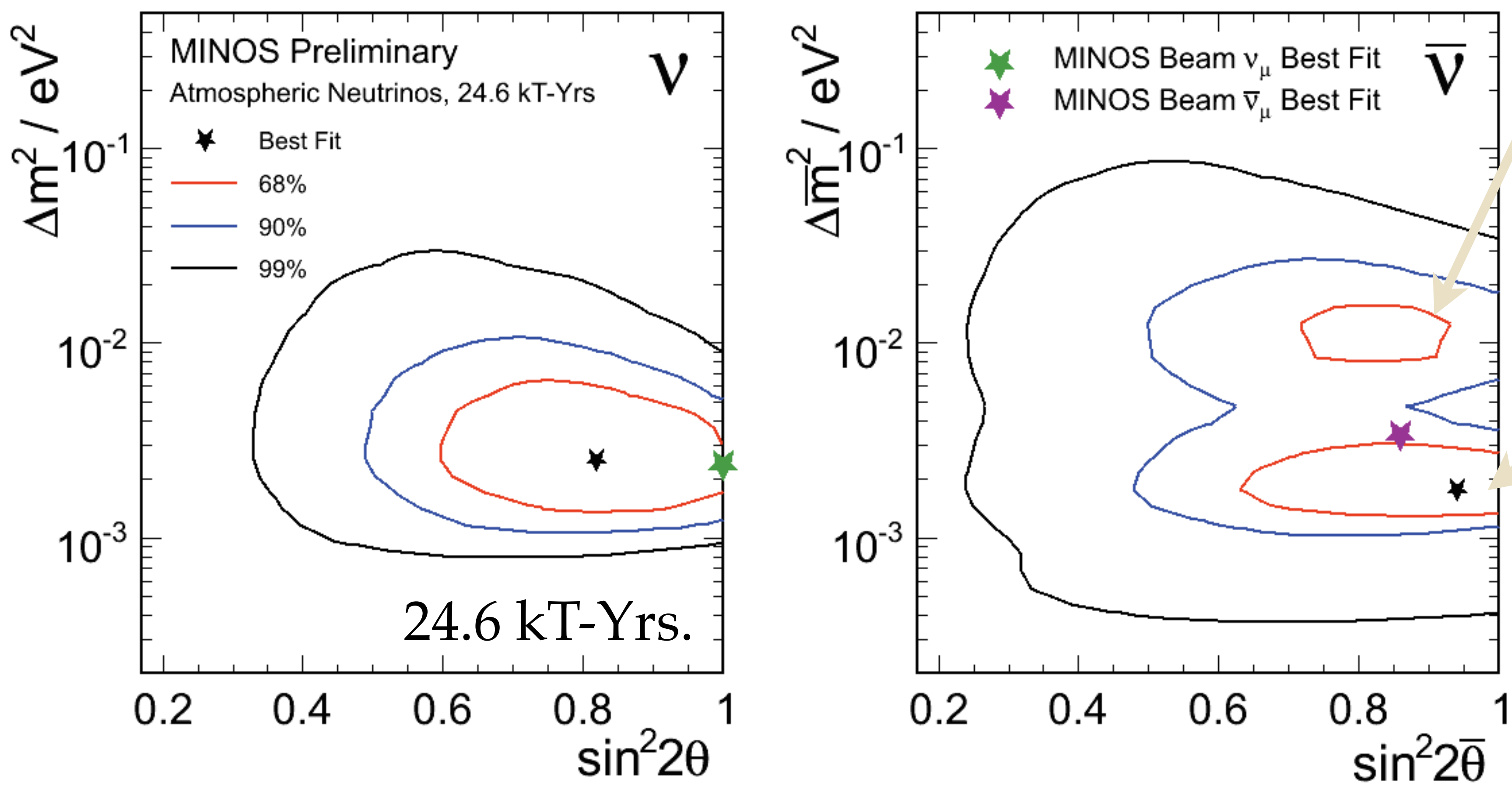
Data



- Divide the data into events with ν interactions contained in the detector and events in the rock producing upward going muons.
- Perform a maximum likelihood fit to the L/E distributions to obtain oscillation parameters.

$$|\Delta m^2| = 2.6^{+4.4}_{-1.3} \times 10^{-3}\mathrm{eV}^2$$

$$7 \times 10^{-3} < \frac{|\Delta \overline{m}^2|}{\mathrm{eV}^2} < 17 \times 10^{-3}$$



$$|\Delta \overline{m}^2| = 1.8^{+1.5}_{-0.6} \times 10^{-3}\ \mathrm{eV}^2$$

http://indico.cern.ch/getFile.py/access?contribId=276&sessionId=55&resId=0&materialId=poster&confId=73513

$$\sin^2(2\theta) > 0.58$$

$$\sin^2(2\bar{\theta}) \quad 0\ 6$$

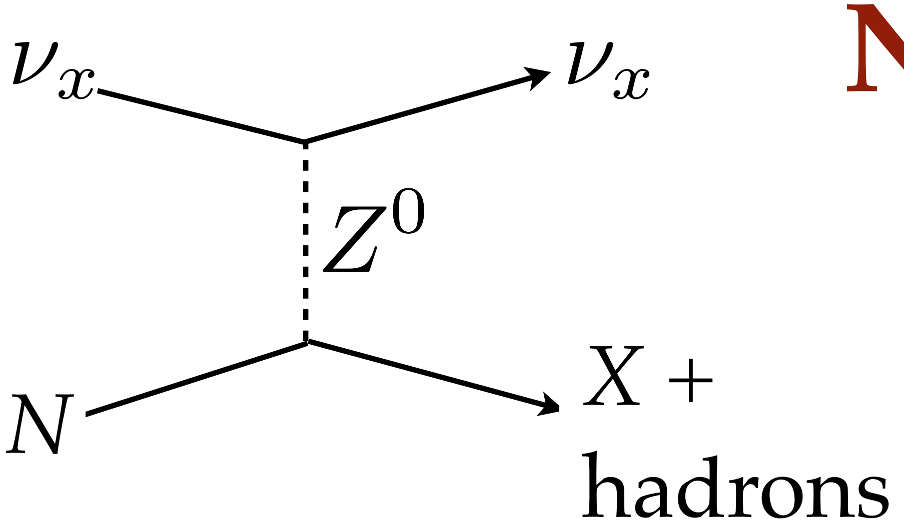
- For ν sample, we fix the ν̄ parameters to the the MINOS ν best fit oscillation parameters from 2008.
- Then, we perform the opposite analysis for our ν̄ sample.
- 35 kT-yr. data set with 4 parameter fit coming soon

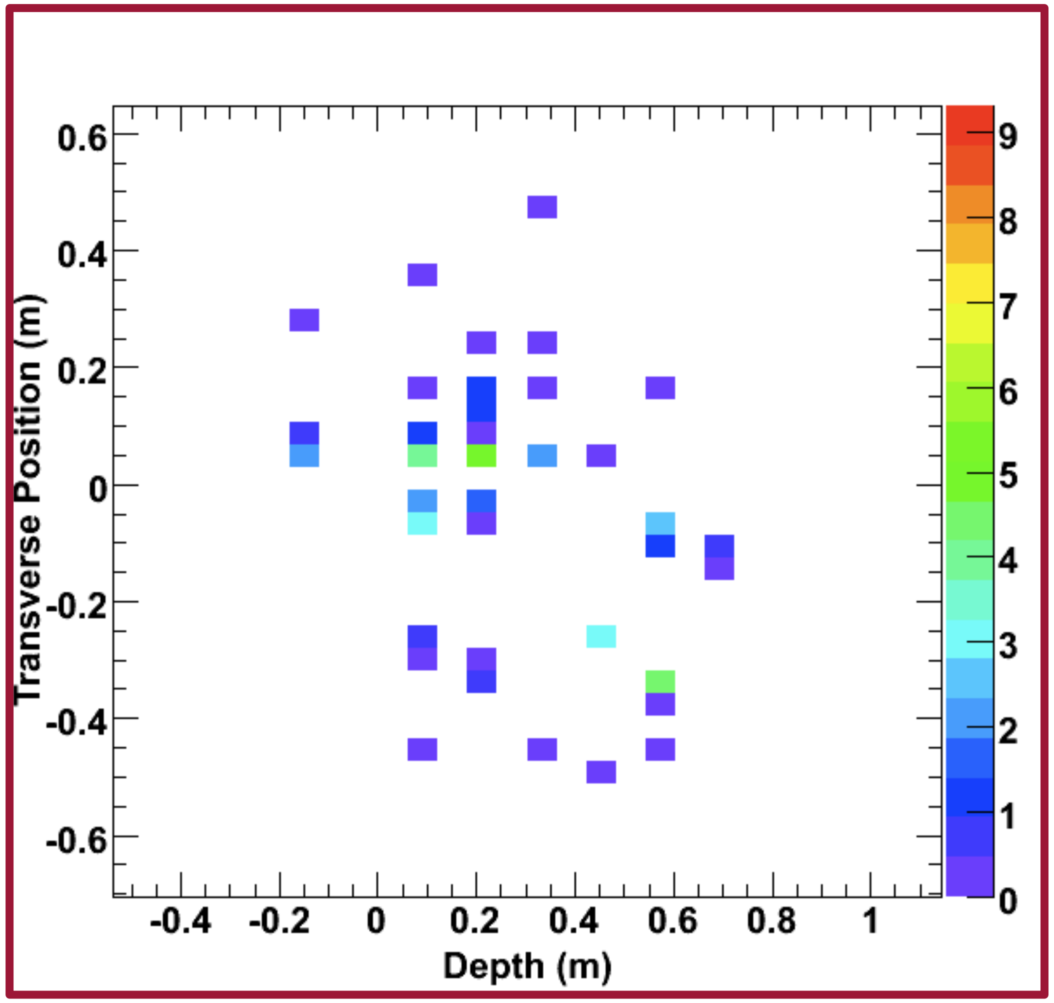
The Future

- New antineutrino analysis with at least doubled data set
- New electron neutrino result with more data and analysis improvements
- New quasi-elastic M_A measurement
- Update atmospheric neutrino results
- Discussing running MINOS in the NOvA beam
- Thank you!

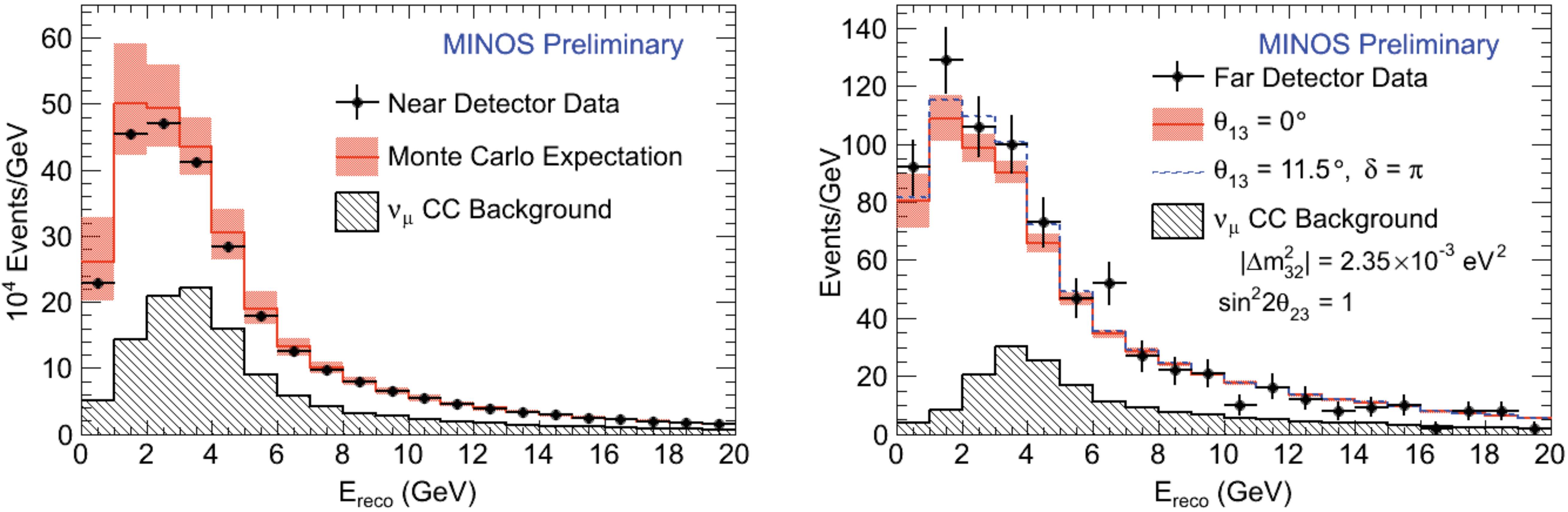
Backup Slides

Neutral Current





- All neutrinos interact via NC
- Far Det. event rate independent of standard oscillations
- Deficit would be evidence of mixing into sterile neutrinos (ν_s)



$$f_s \equiv \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)} < \left\{ \begin{array}{l} 0.22 \text{ (90\% C.L. without } \nu_e \text{ appearance)} \\ 0.40 \text{ (90\% C.L. with } \nu_e \text{ appearance)} \end{array} \right\}$$

- R (Data - Expected Background) / Expected Signal

$$R = 1.09 \pm 0.06(stat.) \pm 0.05(syst.)^{+0.00}_{-0.08}(\nu_e)$$

- No evidence of depletion of NC events

Cosmic Ray Charge Ratio

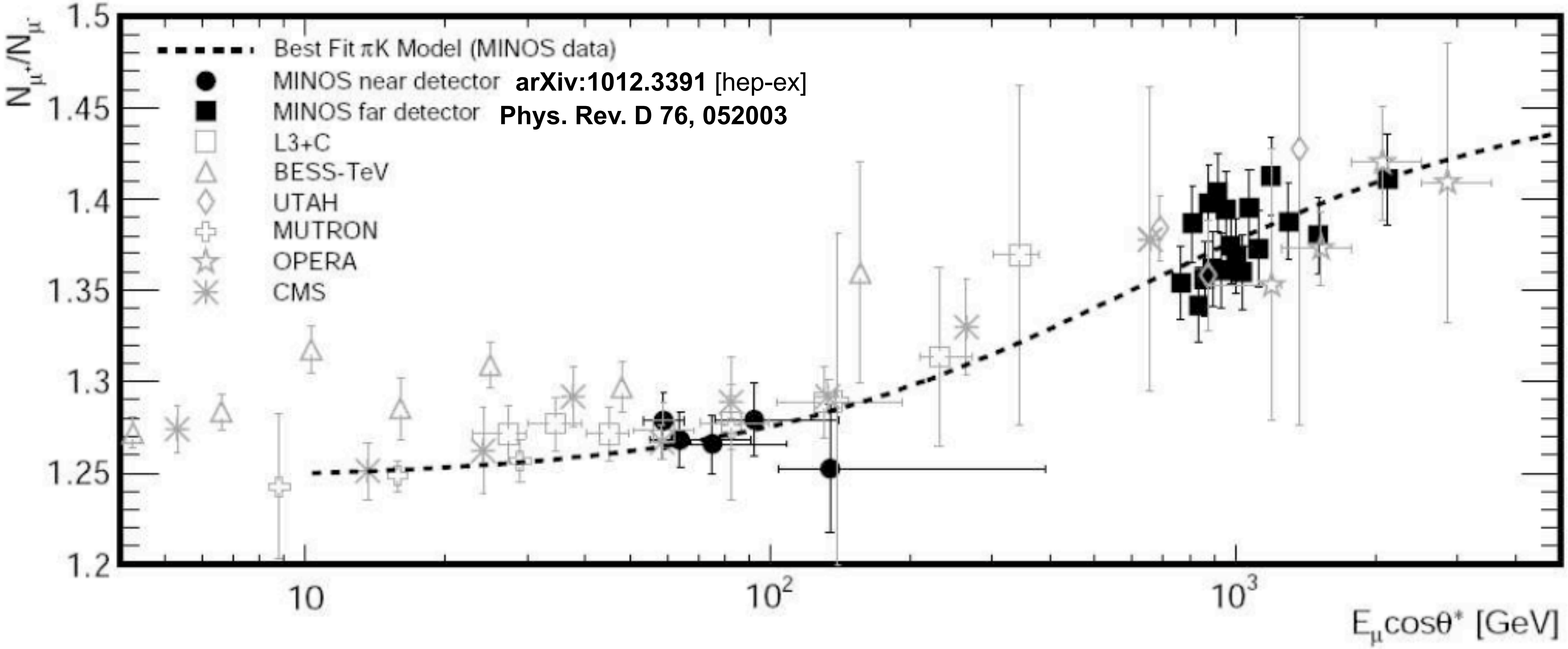
- Use far and near detectors to test simple parameterization of the charge ratio.

Fraction of all decaying pions and kaons which decay with a detected μ^+

$$\frac{N_{\mu^+}}{N_{\mu^-}} = \frac{\frac{f_\pi}{1+1.1E_\mu \cos(\theta^*)/\epsilon_\pi} + \frac{0.054\times f_K}{1+1.1E_\mu \cos(\theta^*)/\epsilon_K}}{\frac{1-f_\pi}{1+1.1E_\mu \cos(\theta^*)/\epsilon_\pi} + \frac{0.054\times(1-f_K)}{1+1.1E_\mu \cos(\theta^*)/\epsilon_K}}$$

Zenith angle at the μ production point

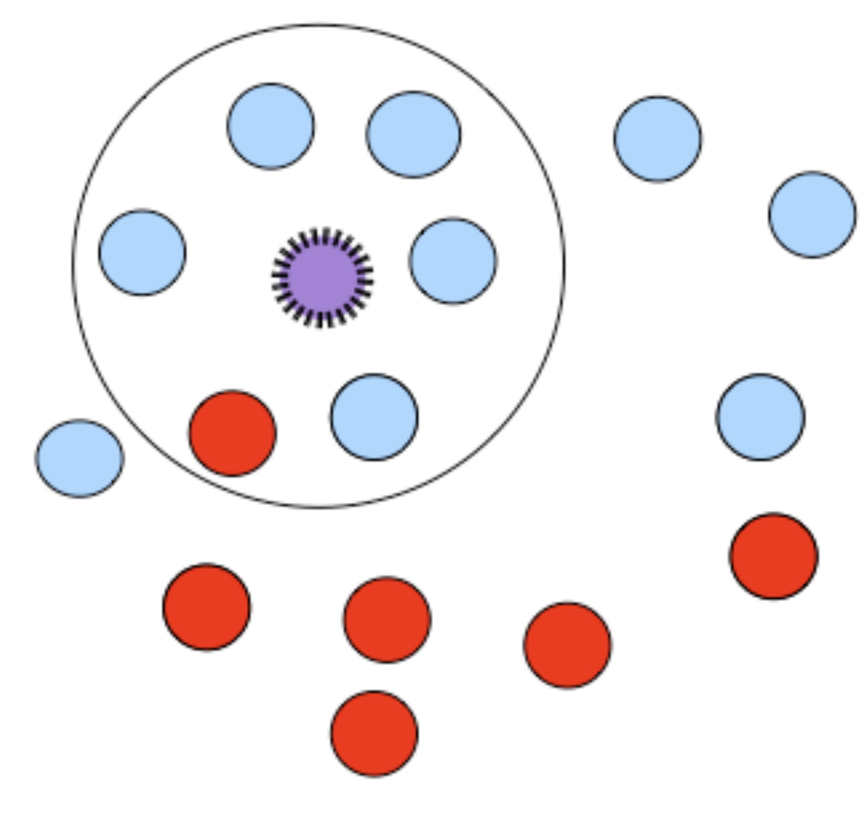
$\epsilon_\pi = 115$ GeV and $\epsilon_K = 850$ GeV are the critical energies at the muon production height above which the pion and kaon interaction probability exceeds the decay probability.

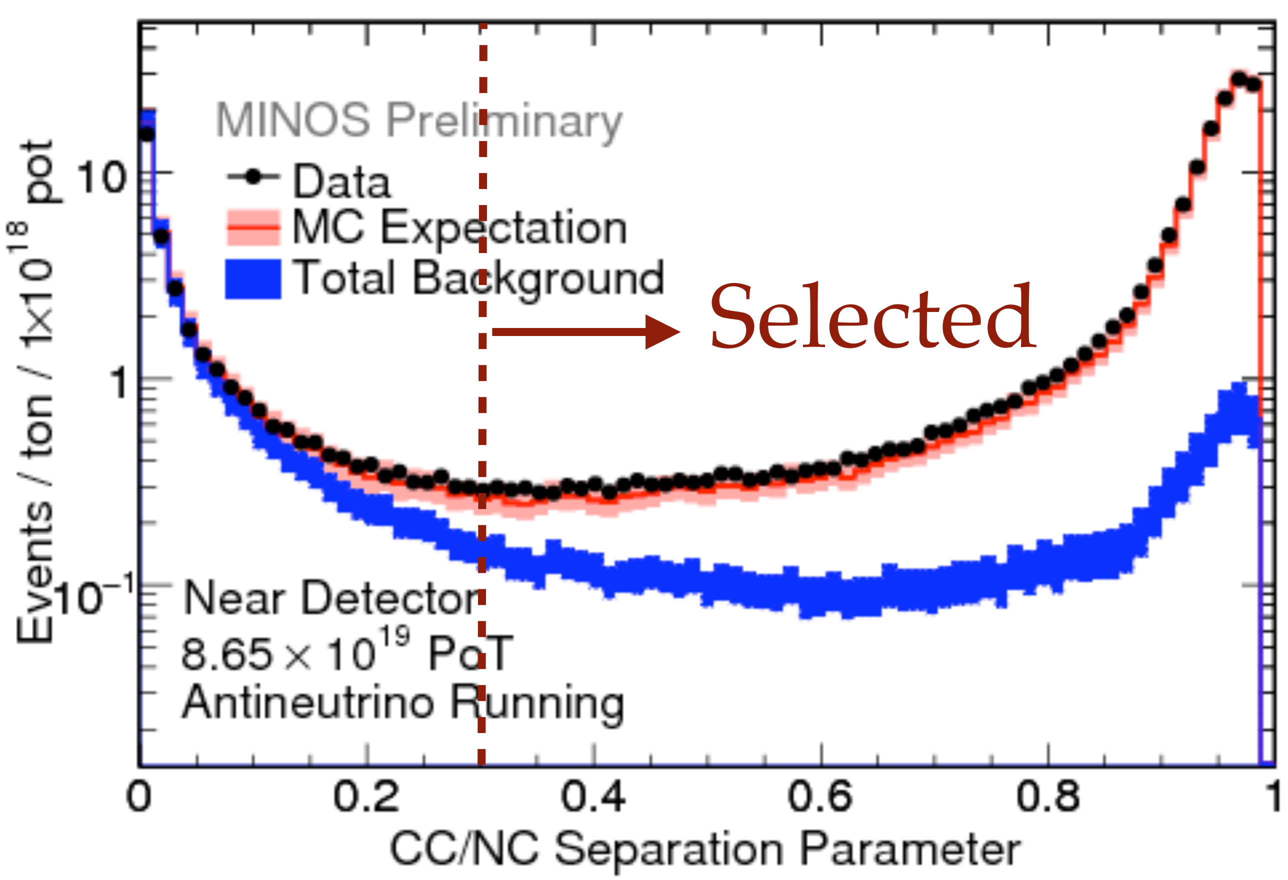


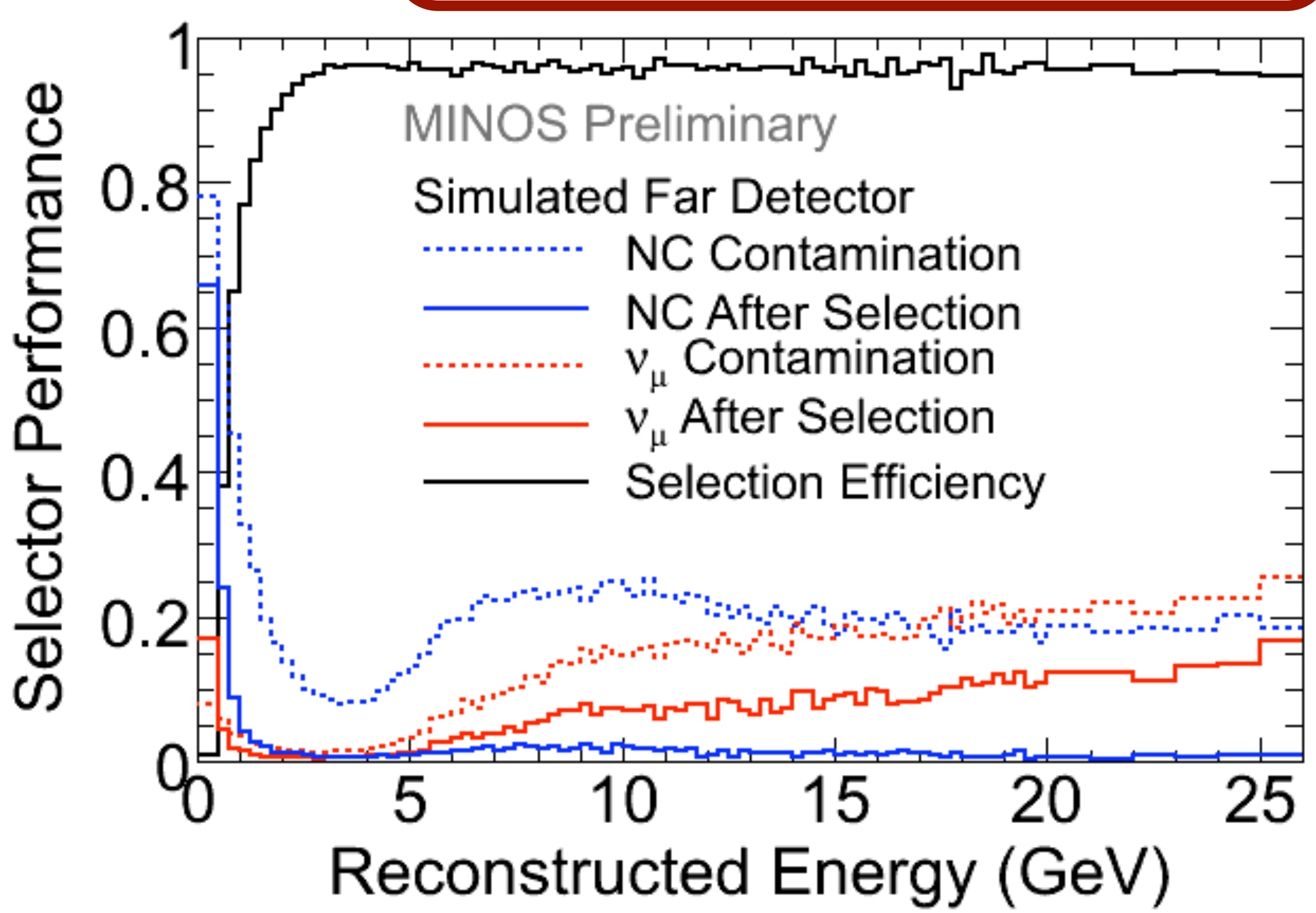
- Data from these and other detectors matches the model well $f_\pi = 0.55 \qquad f_K = 0.70$
- Near: $N_{\mu^+}/N_{\mu^-} = 1.266 \pm 0.001^{+0.015}_{-0.014}$
- Far: $N_{\mu^+}/N_{\mu^-} = 1.374 \pm 0.004^{+0.012}_{-0.010}$

Signal/BG Separation

- Use a kNN algorithm for NC/CC separation
- Integrated efficiency of 93% and purity of 94% at the Far Detector

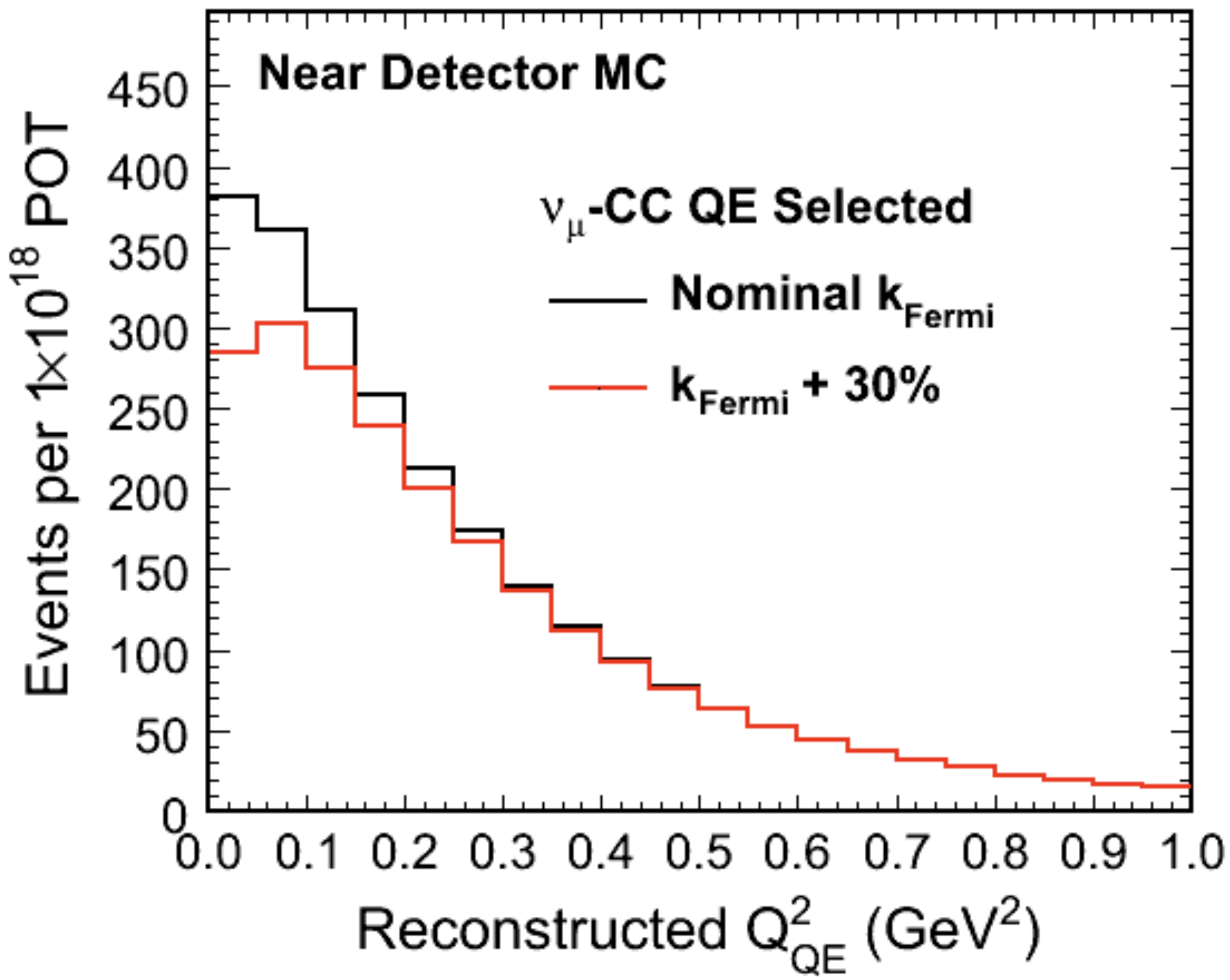




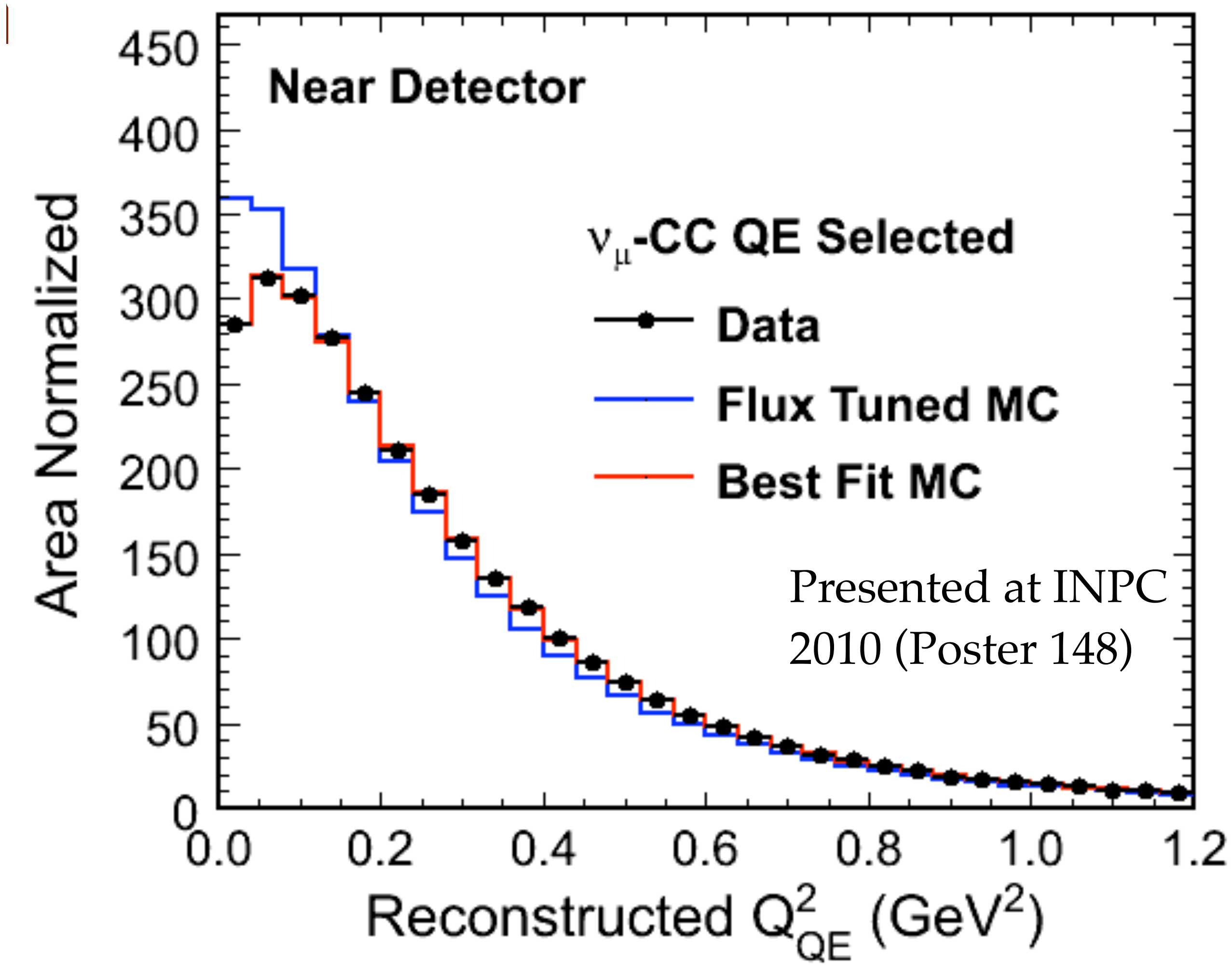


Other Analyses

- The physics reach of MINOS is so rich, there are still analyses I have not had time to cover
  - *Phys. Rev. D* **76**, 072005: "Measurement of neutrino velocity with the MINOS detectors and NuMI neutrino beam"
  - *Phys. Rev. Lett*. **101**, 151601: "Testing Lorentz Invariance and CPT Conservation with NuMI Neutrinos in the MINOS Near Detector"
  - *Geophysical Research Letters*, **36**, L05809: "Sudden stratospheric warmings seen in MINOS deep underground muon data"
  - *Phys. Rev. D* **81**, 012001: "Observation of muon intensity variations by season with the MINOS far detector"



Increase k_{Fermi}, which controls Pauli blocking in the nucleus



$$M_A^{QE} = 1.19^{+0.09+0.12}_{-0.10-0.14}$$

- Greatest difficulty is modeling low Q^2 region
- This sample has only single muon tracks
- New analysis will use samples that include protons and other multi-track topologies